Classroom Façade Design for Daylighting in a Tropical Hot-humid Climate

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Master in Philosophy

by

Sureepan Supansomboon

March 2019

Thesis Title: Classroom Façade Design for Daylighting in a Tropical Hot-humid Climate
Author: Sureepan Supansomboon
Supervisor: Professor Steve Sharples
Year: 2019

Abstract

Previous studies have confirmed that the learning performance of school students can improve when good levels of daylight are available in classrooms. In tropical climates, it might be difficult to utilise and control natural light due to its high levels. Various activities in classrooms, such as taking notes and viewing screens and whiteboard, can also become difficult. Consequently, daylight in tropical classrooms may be less welcome and utilised less frequently. In order to deal with natural light utilisation, building facade is one of significant architectural design elements influencing energy consumption and human comfort.

This study aims to investigate classroom facade designs that attempt to optimise visual and thermal comfort while reducing energy consumption. Focusing on facade appearance, daylighting systems and occupants' behaviour, there are three stages of study using occupants and classrooms in the Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University, Thailand as the case study. The research commenced the first stage with finding the actual problems of daylight utilisation in tropical classrooms in terms of room form, brightness levels, and users' behaviours and attitudes. In order to study brightness pattern and human sensation several survey methods: illumination measurements, observations, questionnaires and interviews; were applied. In the second stage, computer simulation was undertaken in order to analyse the problems and suggest solutions using DesignBuilder package. The suggestions were verified in the last stage by surveying occupants' satisfaction comparing the modified classroom to the existing classrooms.

The measurements and surveys demonstrated availability of the daylight and positive attitude in using natural light of the occupants whereas façade and systems are not appropriated for applying natural light: provided insufficient daylight level and allowed occurrence of glare. Daylight environment appeared to proper for general visual tasks while more control was required for using projector. The simulation result showed the significance of window area, shading device and window orientation respectively. The use of two opposite fully glazed walls with shading depth of 50% of optimised device is recommended for all orientations. The suggested size of shading device usually allowed penetration of the sun into the classroom. The influence of direct sun which theoretically could be a serious problem was confirmed acceptable by occupants. It implies that direct sunlight can rather be a daylighting opportunity if correct shading design is applied. A limitation of this research is that, although the DesignBuilder package can facilitate study in both daylighting and thermal aspects, its daylighting analysis function has limit capacity for light reflected strategies.

Results of this research are recommendations of facade characteristics and their operation systems which are suitable for the case study. The visually environmental improvement of one specific building which can be adapted for general classrooms and other types of low maintenance buildings. Moreover, research findings can be extended to be public guidelines for designers in their approach to sustainability.

Declaration

I hereby certify that this thesis constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Sureepan Supansomboon

March 2019

Acknowledgements

This study was supported by the Royal Thai Government in terms of fully funded scholarship including general assistance which was provided by Office of Educational Affairs, the Royal Thai Embassy UK. Office of the Civil Service Commission was also supportive for general facilitating and coordinating with involved institutes. Mahasarakham University, my original affiliation, additionally sponsored the study by providing permission to study for full time with earnings. As the owner of the case study building which all surveys and measurement were obtained, the university was willing to facilitate data collecting leading to working expedient.

I would like to express my sincere gratitude to Professor Steve Sharples for his kindness to be my supervisor and his patience supervising me with overwhelming amounts of meetings as my request. He has been very supportive and understanding. He always helps with not only research materials and devices but also my terrible language. Working with him, I was allowed to work independently with his guarantees that I would not get lost. He is the best person ever in the UK for me since my arriving day until now. His words “you just come to learn how to do research with me” could make the way to know ‘what is PhD’ in the UK context easier. I also have learnt from two of my viva examiners: Professor Nick Baker and Dr.David Chow. Thank you so much for your intensive advices.

For data collection stage, I would like to thank all participants who are my colleagues and students from Faculty of Architecture Urban Design and Creative Arts for wholehearted participation and their useful comments. The task would not be success without the key persons of the faculty: Assistant Professor Dr. Tarawut Boonlua and Assistant Professor Dr.Pechladda Pechpakdee, the dean and vice dean at that time. I am also grateful to staffs of administration office for facilitating uses of classrooms and providing helpful data of the building and building users. Although it was limit of time, all work was perfectly completed with help from two diligent research assistants: Dr.Supitcha Supansomboon and Aj.Rutchanoophan Kamsingsri. This includes participants and building owners of the additional case studies: Faculty of Architecture, Khon kaen University; Faculty of Sciences, Srinakharinwirot University; Faculty of Sciences and Technology, Chiang Rai Rajabhat University; Prince of Songkla University, Phuket Campus. I also would like to thank you Assistant Professor Dr.Noppadol Tangsakul, Assistant Professor Dr.Sanchai Santiwas, Assistant Professor Nitiwadee

TongPong, Dr.Farung Surina, Aj.Sorowit Upakut and Dr.Kwankamon Dittakan for your kindness facilitating the surveys.

I am grateful for all supports and encouragements from not only lecturers, staffs, classmates and PhD colleagues who involved my study in University of Liverpool but also friends especially from Liverpool Thai Society and contacts in all social networks. In particular, I am thankful for Dr.Pimolsiri Projongsarn and her lovely family. My study would not start properly without their support. Last but not least, it is more than thank you to say to my out of this world family who are extremely helpful at all times. Thank you for believing in me. We might rarely be together, but I know that all of you never stand where else but by my side. Consequently, I can confirm that you are always one of the most important parts in every single step of my success.

Table of contents

List of tables

List of figures

Chapter 1

Introduction

This study attempts to research the utilization of natural light in educational buildings in a tropical hot-humid climate. Previous research has confirmed the importance of natural light in student learning performance. Façade design was focused in this study due to the fact that it is one of the significant architectural elements that impacts upon building appearance and is also the main controller and moderator of daylight. The significance and difficulties of daylighting for classrooms in tropical climates will be presented in this chapter.

1.1 Research topic

The current crisis relating to global warming has had a considerable impact on architectural design, as architects have been forced to become more cautious in terms of ecological effects and sustainability. From an architectural point of view, how people can continue to be comfortable in the building is a great challenge, especially when climate is predicted to change. Being comfortable means buildings inevitably have to consume natural resources during their construction and operational stages. It is generally accepted that buildings are one of the critical causes of environmental issues those resources are depleted. Moskow (2008) stated that far from style or aesthetic, sustainable design involves ethics. While architects are responsible for occupants' living quality, natural resources also need to be preserved.

Energy, which is one of the most important resource inputs to a building, is now produced mainly by non-renewable resources. Without appropriate knowledge of climate in architecture, various differences between weather conditions and human requirements possibly lead to high level of energy consumption in buildings in order to satisfy occupants. Recently, the term "Indoor Environment Quality (IEQ)" has been introduced as part of design criteria. Several strategies regarding energy conservation and IEQ are being created and applied to tackle these environmental issues. IEQ consists of Indoor Air Quality (IAQ), and thermal, visual and acoustic comfort, which can be standardised by proper design and operation (FFC, 2005). Air conditioning and electric lighting systems, which essentially impact upon thermal and visual issues, normally bring about the majority of energy use in buildings in most cases (Kong et al., 2012).

For achieving comfort in most climates, complicated technologies have been offered to convert renewable resources to electric power supplying the equipment. Solar radiation is a resource that can be utilised instantly for heating and lighting internal spaces without significant environmental impact. However, in hot climates, natural light excluding heat can benefit not only occupants' comfort but also energy conservation. Careful architectural design is essential when using daylighting in the Tropics.

1) Importance of natural light

It has been broadly known that lighting generally affects human being in terms of health and wellbeing. Light intensity and its colour temperature influence human physically – for example, their blood pressure, heart rate and core body temperature. The higher lighting quality provided the better dental health and physical growth of students. Psychologically, different qualities of light can cause create different moods. Learning performance and academic achievement can also improve in sunlit and daylit classrooms. Alertness, attendance and concentration can be facilitated by improving the visual environment. Good quality light, even artificial light, provides positive effects on working speed and accuracy. Sleegers et al. (2012) found that a lighting environment that is brighter than a standard lit environment benefits students' reading, writing and mathematics skills. Dynamic lighting higher better visual performance and arousal.

According to Altomonte (2009) natural light is not different to artificial light in terms of its electromagnetic quality. However, natural light is not only very bright but also dynamic. In daylighting conditions occupant vision was improved because of high illumination level and colour accuracy resulting from high contrast of highlight and shadow (Heschong et al., 2002). Daylight's spectrum guarantees excellent colour rendering, which provides visual accuracy (Boyce et al., 2003). Daylight colour is the most compatible to the human visual response (Li and Lam, 2003). Natural light has been considered as the best light source for visual performance.

The enrichment of people's health and performance occurs in suitable natural light, revealing the worth of daylighting. A lack of daylight can cause either gradual eye damage in an insufficient light environment or the frequently use of artificial light can cause occupants' illness called 'sick building syndrome' (Smith, 2005). Halliday (2008) also showed results of a study in Norway that non-daylit classrooms caused a negative effect on the physical growth and emotional habits of the students, while the students' health in daylighting condition were better. According to classroom research (Halliday, 2008), natural light provided a positive mood for the students in terms of their concentration and interacting ability. Moskow (2008) illustrated the results from the National Outdoor Leadership School Headquarters that working space with natural light can encourage worker cooperation.

Ulrich (1984) stated that a view through a window may influence recovery from surgery. Windows provide environmental contact, which meets people's psychological needs and leads to human wellbeing. In terms of working performance, it is suggested that an environmental connection is required in the working area even though less windows appear to cause occupants to concentrate more on their work. In order to support this idea, Yudelson (2007) demonstrated in the USA that the students in daylit classrooms with outdoor views had a higher learning performance than those in windowless conditions.

Good levels of natural light are readily available for most of the day tropical climates and are generally welcomed by building users. Evidence from non-domestic buildings in Hong Kong illustrated that in users' satisfaction and performance surveys daylighting was found to be more important than energy savings (Wu and Ng, 2003), although energy conservation still an important benefit of natural light. Replacing part of the artificial lighting demand with natural light can save energy without additional cost. The study by Chirarattananon et al. (1996), for example, showed a 50% reduction in lighting energy consumption was for a building in Thailand. With no need for complicated equipment or maintenance, the natural light can be simply applied to building interior spaces through the façade. As a renewable resource that provides health and well-being, improves working performance, enhances visual comfort and saves energy daylight is certainly a substantial component in sustainable design. However, it is complicate to deal with applying natural light to a building because daylight is welcome only if it is in proper amount and quality.

2) Role of façade

In terms of man-made shelters, architecture had been developed intensively both for security and human comfort. The building envelope represents a system of external skins, such as outer walls and roofs, in each building (Harris, 2005). As one of the most important elements that forms the building shape, the envelope also plays a key role in reducing the climatic influences on occupants. In terms of character and aesthetic, the façade is one of the key elements in terms of a building's appearance. The façade also plays a principal role of providing security and shelter from the weather. The importance of façade features was shown by Le Hong and Rodriques (2013) for improving the visual and thermal performance of a building in the UK.

Significant elements of a façade for daylighting include windows and shading elements. For the interaction between building space and outside the facade engages with thermal, daylighting, acoustics, outside interaction and aesthetic (Boneh, 1982). In terms of daylighting, the façade can maximize use of natural light while controlling heat and glare leading to users' comfort. Psychologically, people need different facade designs for either privacy or good view using space activities and personal preference as criteria (Markus, 1967).

In terms of architectural design, the façade is an important interface that mainly relate to daylighting design. Therefore, properly designed façade features are always questioned for compromising between lighting quality and heat and glare control.

1.2 Current state of knowledge

This research is interested in educational building type which has simple manual controls and low maintenance. Although many pieces of research (e.g. Yudelson, 2007; Halliday, 2008 and Moskow, 2008) have confirmed that the learning performance of school students can improve when good levels of daylight are available in classrooms, daylight is less welcome in tropical climates, where it might be difficult to utilise and control natural light due to a very bright sun and sky. Various activities in classrooms, such as taking notes and viewing screens and whiteboard, can also become difficult. Conflicts and difficulties were found when studying previous research.

1) Daylighting and classroom

Proper lighting environment was confirmed that have very significant impact on students' learning performance (Samani and Samani, 2012). It is not only appropriate lighting conditions can enhance students' productivity and performance but improper conditions also resulted in negative effect. Montenegro et al. (2012) concluded that visual environments can have the most significant impact on typologies of school building comparing to other environmental aspects. Lighting comfort was suggested to be considered before making decision on classroom shape. According to Barrett et al. (2013), light was the only influential factor on students' academic achievement when a range environmental factors (light, sound, temperature and air quality) were investigated.

a. Impact of daylighting in the learning environment

Some studies attempted to prioritise environmental parameters. Lee et al. (2012) found that Indoor Environmental Quality (IEQ) was strongly associated with university students' learning performance. The visual environment was rated significant after aural and thermal aspects. As another point of view, Theodorson (2009) stated that teachers rated natural light and view as benefiting learning environment the most compared to temperature and humidity control, good ventilation and artificial light control. Barrett et al. (2015) supports the priority of lighting when seven influential design parameters for daylighting in classrooms: light, temperature, Indoor Air Quality (IAQ), ownership, flexibility, complexity and colour were investigated. Lighting was ranked as having the highest impact compared to other parameters. Lighting was investigated as one of key components in classrooms, either natural or artificial (Leung and Fung, 2005). When different types of artificial light were compared in the long term by Hathaway et al. (1992) and Hathaway (1995), full spectrum fluorescent lamps with ultraviolet supplement had a positive effect on physical growth, health and academic achievement of students. It might be due to the fact that the lamps colour is very close to daylight with a colour temperature 5,500K of and a colour rendering index of 91.

Many pieces of research show that daylight plays a very important role in classrooms. Students and teachers' performances were developed as daylight can not only facilitate memory retention but also result in better mental stimulation and alertness while also having a calming effect. Students' health is proved can be enhanced in the long term (Heschong et al., 2002). Tanner (2009) found that natural light and a view from a window significantly benefited students' skills in reading, language arts, mathematics and science.

However, an appropriate quality of the daylight is required. Classrooms with regularly adequate and uniform daylighting were found to have the highest rate of academic growth (Heschong et al., 2002). Bright light can facilitate people's well-being but too much sunlight can create uncomfortable glare for both teachers and students, especially during the summer (Leung and Fung, 2005) .

According to her research survey, Denan (2004) rated that improper window design is one of the most important causes of dissatisfaction with daylighting. According to Wu and Ng (2003), there was an idea to minimize window areas in the 1960s for to two main reasons. Firstly, it was believed that students' attention and their reading concentration can be distracted by an outside view and daylight fluctuations, especially the impact of direct sun. Secondly, large window areas generally provide excessive high illuminance and heat gain, leading to visual discomfort and high energy consumption respectively. With the widespread application of fluorescent and air conditioning systems, the concept of windowless classrooms was raised and implemented for a while. However, many pieces of research argued the concept of windowed classroom was the preference of the majority of students. A preference for window was also revealed when most students tended to select their seat near to windows, mainly because of daylight and view respectively (Stewart, 1981). There was evidence claiming that when, compared to windowed classroom, windowless classrooms did not cause a significant difference in terms of learning performance and health while another study affirmed the change to windowless classroom probably affected more frequent absence of younger students and caused complaints from older students. However, one of researchers who confirmed that windowless classrooms had no negative effect in students' performance also noted that the long-term effect of this result has not be approved. Wu and Ng (2003) presented some drawbacks of windowless classrooms, saying that it had negative effects to students' hormones according to long-term research in Sweden. It can not only reduce concentration and co-operation abilities but also influence their body growth and sickness.

Apart from illuminance needs, Theodorson (2009) found that a better view had a positive effect on student performance. Demonstrating the benefit of adding eye level window that can cause lower eye fatigue than using skylight alone, Wu and Ng (2003) supported the advantages of windows in terms of environmental contact.

For daylighting, a window's size was reported as having an insignificant correlation with students' learning progress unless its orientation and glare protection was concurrently considered. Many suggestions with different conditions were recommended but they appear cannot be generalised as each of them was too specific. While daylighting elements appear too complicated to assess, artificial light become the easier choice. Artificial light may consume energy, was generally found to be oversized and had improper controls, but good quantity and proper quality of artificial light was affirmed to also benefit learning performance.

b. Difficulties of daylighting in tropical climates

Daylighting in tropical climates contains three major difficulties: extreme fluctuation, optimisation of daylighting and heat protection, and lack of specific design guidelines.

According to Maitreya (1979), daylight levels were generally inadequate in classrooms in a hot humid climate. This may be because of the inefficiency of daylighting systems; also, to maximize the transfer of natural light is complicated in tropical areas. For hot climates large areas of windows definitely provide high daylight levels and reduce the use of artificial light, but excessive heat gain can have negative effect on energy consumption due to the fact that it increases cooling load. The application of artificial lighting appears to be an easier solution since it has less impact as cooling energy dominates overall energy consumption of buildings (David et al., 2011).

For warm climates, daylighting brings not only less lighting load but also cooling loads are not as much of of an issue. The obvious differences reveal that specific strategies are required for different climates. Developments of facade systems for daylighting are prevalent mostly in temperate climate areas, especially in Europe and North America, but rare in hot climates. Hot-humid climates are normally located near the Equator, where solar radiation influences are extreme and the sky is very bright (Zain-Ahmed et al., 2002). Practical knowledge of architectural daylight design is frequently for warm climate conditions, whereas there are still questions for tropical zones, according to Wu and Ng (2003), Tregenza, 2003) and Denan (2004). It is not only different of climates but also people's habits that result in a considerable diversity of comfort and energy consumption in different areas of the world (Alrubaih et al., 2013). People's behaviour can be caused by many factors, such as ethnic identity and cultural uniqueness. The difficulty appears to be more complicated when different building types significantly influence occupants' behavior. There is evidence that even if the climate is similar, considerable numbers of discrepancies may be found. Although daylighting has been intensively researched for a long time Baker and Bernstein (2012) still suggest more specific research and guidance for architectural design in USA. Consequently, existing findings may not be immediately applied to other specific conditions.

These difficulties reveal that for daylighting in specific contexts for tropical climates there are still gaps in knowledge. For the preliminary stage of design general guidance for daylighting in specific building types is required for tropical climates. However, more focused study appears essential for more complicated design guidance.

c. Conflicts of lighting requirement

Lighting levels for specific conditions and tasks are recommended by various lighting guides. For classrooms, existing recommendations of between 300-500 lux are widely recommended. Since technological teaching devices (whiteboards, projectors etc.) were introduced to classrooms, the demands on the lighting environment have become much greater range. While a substantial brighter environment is a general condition of daylighting, a dimmer environment is required for using the devices. In addition, classrooms contain different activities which require separate lighting requirements. The conflict results in the needs of switching lighting environment.

Daylighting quantity and quality and integration with artificial lighting are important and have complicated relationships. The application of natural light in multi-function classrooms can cause daylighting more difficult.

d. Satisfaction and attitude

Occupants' attitude can be one of difficulties for daylighting, especially when manual control is required. There are some conflicts found where the occupants' attitude can be one of the barriers to daylighting. In general, daylight has been considered to satisfy students' visual comfort and have a significant impact on students, learning performance. As Yang et al. (2013) report, when students were asked to vote for their opinion regarding the influence of classroom factors on their satisfaction, lighting appeared less significant. Considering colour, glare and illuminance level, the majority of occupants voted that they were satisfied with the lighting. These findings appear not to agree with other studies which might be due to the fact that university classrooms and older students are totally different to school classroom and young students. Moreover, it may be because the persons who reported the results are different. Older students can inform their opinion themselves while teachers reported their young students' behaviour.

Occupants' opinion about impact can only show what they think, which is possibly not always true. It is possible that visual satisfaction results in positive effect on students' learning performance but the students may not realize this while teachers do. Long term monitoring research such as that by Barrett et al. (2013) appears more sensible and can better verify the impact of the light environment on classrooms because the outcomes were educational achievement rather than subjective assessment.

Most evidence implies that daylighting benefits both satisfaction and performance but different methods are required for investigating them. In addition, a conflict of students' votes reveals the risk of daylighting ignorance as it was perceived to be unimportant.

2) Development of facade

Attempting to face daylight fluctuations, many developed countries suggested the integration of adaptive materials and automatic systems leading to convenience and effectiveness, for example Smith (2005), Bell and Kim (2009) and Tilder and Blostein (2009). The changes of facade system can optimise thermal comfort and light quality - for example, for a bright summer sky three major systems can be synchronised: shading devices expanded, electric light dimmed and then room temperature is decreased by cooling systems. Whereas Tilder and Blostein (2009) indicated that the high technological facade with integrated building automations is more effective than passive systems; Knaack and Klein (2009) pointed out that because of high technological processes, the envelopes are expensive and use a high rate of energy in their production process, including transportation. However, Birkeland (2002) argued that the costs are reasonable when considered in the long-term. In spite of solvable issues regarding cost, Knaack and Klein (2009) argued that these complicated solutions required experts thorough their life cycle. However, Elkadi (2006) believed that those weaknesses could be improved in the near future. Some researchers have examined these systems and found recent improvements in innovative systems; for example, horizontal automated blinds (Chaiwiwatworakul et al., 2009); prism glazing (Knaack and Klein, 2009); photovoltaics glazing (Smith, 2005) and anidolic integrating ceiling daylighting systems (Linhart et al., 2010).

These innovative systems are being developed and discussed, and may be appropriate for some building types, such as office buildings, where functions and operational hours are consistent. While several studies have focused on commercial buildings and advanced lighting systems, it is claimed that energy consumption in each building is different due to individual building type, location, operation and ownership type (Yudelson, 2007). According to several recommendations, such as BREEAM New Construction manual (BRE, 2011), access for occupants to control systems manually is one of the suggestions in education buildings. Although it has been stated that daylighting cannot be successful unless artificial lighting and its control system were integrated (Alrubaih et al., 2013), it appears that high technology facade cannot be applied to some types of building, for instance non-commercial or public buildings which belong to low profit organizations. For these types of building simple control and low maintenance are needed.

Focusing on daylighting in classrooms, previous research can be divided into two approaches: occupants' behaviour in using daylight and efficiency of façade features. The topics appear separate and complicated to simultaneously examine but for the manually operated type of façade the participation of occupants' was found necessary for façade application.

3) Different focus of previous research

Existing studies have illustrated the importance of design appearance, building system and occupant behavior in visual comfort and energy use, but they generally focused on specific parameters. According to the review from da Silva et al. (2012), knowledge of daylighting in terms of solar radiation effect has been studied in different ways. Each pieces of research was developed under a very specific context. For example, Andersen et al. (2009) studied occupant participations; only sun shade sizes were studied by Ho et al. (2008) while Ihm et al. (2009) focused on lighting systems. Reviewing different perspectives on research, Wu and Ng (2003)concluded that not only was not much evidence found, some knowledge like daylighting quality showed a lack of understanding. Visual comfort was separately examined using different indicators. Assessment of glare, for example, has been lately studied and appears to be able to successfully indicate visual comfort. However, da Silva et al. (2012) argued that it is too limited research to assess just visual comfort as there are other influential factors apart from glare. Users' preference, their response to the lighting environment, including human factors such as brightness perception and familiarity, also have been specified as significant parameters. For design consideration, a holistic perspective is more practical. Consequently, these distinct factors are required to concurrently examine and prioritize in order to deal with design limitations.

In order to study separated parameters, modelled environment are more effective than using real buildings because they can be planned for adapting to several conditions, but when human behaviour and operation method are included, existing constructions are more practical. With the belief that architecture can be created and renovated by studying specific problems, Post-Occupancy Assessments (POE) has been introduced for different issues in specific cases (Halliday, 2008). Many previous studies using POE as their main method revealed the possibility to adopt for understanding focused problems of building utilisation. For instance, Smith (2005) mentioned that this assessment is necessary to examine effectiveness and failure for building improvement. Because of its inclusive viewpoint, the idea of an occupant satisfaction survey compared to real-use monitoring was affirmed to be practical for design improvement (FFC, 2001). This useful concept can be applied to measure impacts of influential factors simultaneously.

1.3 Research questions and aims

Difficulties of daylighting in tropical climates result in many questions, especially for classrooms, where natural light has proven to be highly desirable. The most important problem of daylighting in the Tropics is the lack of applicable guidance - there are many conflicts in research findings and lighting requirements. Daylight is mostly welcome whereas solar radiation and fluctuations in lighting have to be controlled for comfort and energy conservation reasons. Several levels of illuminance are required for different learning activities, for example while the use of presentation equipment is more effective in dim environment, brightness is demanded for student desks. Proper control of facade and lighting has been undertaken as a key solution but automatic system approaches are generally impractical. Manual systems and user participations have been confirmed as more practical. Façade design can optimize daylight while protecting from excessive heat and light levels in various types of learning activities. While specific guidelines have been required, there is a little information to guide architects in the preliminary stages of a design. In order to generalize the solution, investigation of façade design parameter influence and empirical study are required.

This study investigated features of façade design for daylighting in classrooms in hot humid climates. Combinations of façade parameters are to be examined to assess to what extent daylight could be allowed in to a classroom to enhance the lighting whilst limiting heat gain. Before integrating artificial light, the façade should solve major issues of daylighting insufficiency and excessive high illuminance ratio. Influence priority of façade design parameters that can deal with those issues should be investigated. Too various approach and conflicts of previous study result in doubt. Many factors have been mentioned as being important for visual comfort in multi-function classroom. Factors which are not relevant to lighting should be excluded in the first stage. Moreover, lighting requirement conflicts of each function to be compromised are required to be intensive studied. In addition, not only improper façade operation but also existing lighting standards have been found impractical for natural light utilisation. As primary source of information, occupants' viewpoints are necessary for solving the difficulties. In terms of design recommendation, the findings must be confirmed in various aspects including physical assessment, occupants' viewpoints and generalisation.

The main research questions to be addressed were:

1. What are the actual problems of tropical classroom lighting conditions that are relevant to façade design for daylighting?
2. What are the appropriate lighting conditions for each learning activity in multi-function classrooms?
3. How can daylight be utilised in those conditions?
4. What combinations of façade parameters provide good daylight and thermal comfort conditions in the classrooms?

1.4 Methodology

Since the study aims to suggest not only design solutions but also guidelines, the research was planned to use basic processes and simple methods. According to previous studies, and pilot study of the current research, the research methodology was conducted in three stages of study using selected methods which were scoped on the basis of access, software and data logging resources, and time restraints.

1) Three stages of study

The research methodology consists of problem monitoring, solution suggesting and application stages. All stages had been studied and analyses undertaken between October 2011 and March 2015 (details shown in Table1.1)

Tab.1. 1 Research schedule

No.	Stage	Process of study	2011			2012												2013												2014												2015								
			Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1		Literature review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
2		Program study				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																
3	Problem study	Data collection preparation							■																																									
4		Weather data measurement (Thailand)								■	■																														■	■								
5		Survey and measurement (Thailand)								■	■																																							
6		Analysis and Conclusion										■	■																																					
7		Result publication																											■																					
8	Simulation	Case study modelling											■	■																																				
9		Test of setting and pilot study												■	■	■																																		
10		Calibration														■																																		
11		Simulation															■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■													
12		Analysis and Conclusion																																				■	■											
13		Result publication																																							■									
14		Data collection preparation																																						■										
15		Survey and measurement (Thailand)																																							■	■								
16		Analysis and Conclusion																																									■	■						
17		Writing up stage																																											■	■	■	■	■	■

For the problem monitoring stage, preliminary data collection were obtained from classrooms, which contained physical measurements and behaviour and satisfaction surveys, in order to analyse the reasons for visual discomfort in the existing classrooms focusing in failures of facade design and daylighting control. Weather data were studied comparing measured data from weather stations and data generated by software during summer solstice and winter solstice at the case study.

Computer modelling software was studied, selected and used for façade design development in the suggestion stage. In this stage, measurements and predicted results were compared for validation. Due to the fact that a daylighting analysis function of the selected dynamic thermal modelling program, DesignBuilder, was being developed, the program was studied at the same time of simulation. The predictions were repeated and checked periodically when the daylighting analysis function in DesignBuilder was updated.

In the application stage, design alternatives were selected for repeating surveys as a re-check process of simulations. Modified classrooms were set at the same location as the existing classrooms using the room users as survey participants. Measurement was obtained again for calibrating predictions and surveys.

2) Research methods

Methods used in this research consisted of computer simulation, surveys and measurement. For simulation, predictions of thermal comfort, cooling load and daylighting were calculated and compared using DesignBuilder as the main device. The focused parameters arose from discussions in previous studies and problem analysis of the case study. The results of this stage were predictions of each combination of influential façade design parameters for specific dates during school working hours.

Surveys consisted of physical surveys, observation, questionnaires and interviews. The surveys aimed to investigate behaviour, attitude and satisfaction of occupants in the classrooms of the case study. Façade feature parameters may be limited to only existing elements and selected solution but the modelling study can expand to daylighting control which is the parameter that cannot be examined by simulation.

Measurements of this study contain general weather data of the existing and modified classrooms and comparative collections of different façade features and control conditions. The method was applied for not only examining the nature of weather condition of the case study but also facilitating analysis of the other methods. The weather data were used to validate simulation predictions. As they had been concurrently obtained, the qualitative output from the surveys and quantitative data of the measurement were compared and their relationships studied.

3) Scope of study

According to a review of previous work, the research in this topic has been studied using several methods and approaches. This study attempted to apply general daylight concept using basic methods and simple devices which can not only be simply continued to further study but also can be guidelines for studying methods. Representative parameters, indicators, methods and case study were scoped for more focus.

Façade parameters which were focused on in this study consist of façade design appearance and daylighting control systems. There are four influential design parameters: window area, shading device, window orientation and glazing type. Glazing type is not counted in because it does not affect building appearance. Additionally, it can be considered at a later stage of design and improved after buildings are already operating. Because of time limits, details such as types of shading device were excluded. General alternatives like the projecting depth of a horizontal were considered as the most appropriate device to investigate, mainly because of the high tropical sun altitudes. For daylighting control, due to the fact that manual operation of daylighting control is focused, occupants' behavior has to be included for the study.

The research attempts to provide a visually comfortable environment whilst maintaining thermal comfort and reducing energy consumption. Quality and quantity daylighting, Fanger PMV comfort model and cooling load can represent focused indicators. Dealing with daylighting, this study applies working plane horizontal illuminance for quantitative physical factors while illuminance ratio, vertical luminance and ratio and occupancy response are used for qualitative aspects.

The main methods selected in this study are computer simulation, measurement and survey. Simulation technique was applied for investigating impact of façade parameter combinations using DesignBuilder package while survey was arranged for assessing occupants' visual satisfaction. The results were calibrated using illuminance and luminance data of physical measurement.

The Faculty of Architecture, Urban Design and Creative Arts is the case study of this research. The building locates at Mahasakham University in the northeast of Thailand, which experiences a tropical hot-humid climate. Focusing on 60 seat lecture rooms, the regular size of classrooms in Thailand, this study obtained the results of classroom activities' observations, users' opinions, and physical measurement. In addition, the classrooms were modelled for studying façade features at the simulation stage.

1.5 Implementation

The research outcomes of this study can be categorized into three approaches: recommendations of existing façade improvements, new design guidelines and daylighting study process suggestion.

Due to the advantages of simulation, renovation was found feasible for the case study in controlling lighting quantity and quality. Principally, research findings can indicate how to improve both energy conservation and the learning environment of the building where sustainability and good IEQ occur. Whereas simple techniques and low maintenance systems have been implemented, the success which will be achieved can also induce owners to be more concerned about living quality in their buildings. As a result, wellbeing and sustainable architecture can be further developed. Although the results can straightforwardly be used in limited conditions, it can probably be applied to similar contexts.

Identification of the influential factors and indicative characteristics of classroom facade designs can be used to facilitate decision making at the preliminary stage of design in new constructions. Firstly, the ranked priority of influential factors can provide obvious design criteria. For example, if window area is the most significant parameter then architects can apply this knowledge to their design at a very early stage. Secondly, indicative characteristics of a façade can be designated directly in a schematic plan. For example, the suitable dimensions of shading devices could be suggested with its link to window area and orientation. Lastly, the integrated system solution can guide architects to understand its concept for working with engineers. Consequently, all recommendations suggested can benefit designers, building owners and users in general and this outcome can be extended to cope with widespread environmental problems.

Furthermore, the methodology of this research can be directly adapted to other education building and non-commercial public buildings for renovation purpose. For future studies, those findings of different buildings can be compared leading to general guidance for particular building types in tropical climates.

Chapter 2

Literature Review

In this study the literature review is based on façade design for daylighting, specifically in school buildings or classrooms. The topic contains four key words which are: 'daylighting', 'tropical climate', 'façade design' and 'classroom'. This review illustrates general knowledge of daylighting and tropical climates. The knowledge review focuses on daylighting design and classroom façades. The information on daylight availability will be presented specific for a hot humid climate in Thailand. Due to the fact that lack of previous research in the same topic, the studies in the same areas were compiled although they are in other climates and different building types. The views of classroom occupants were also interested. Some general knowledge and findings that are well known but not related to the key words are excluded.

2.1 Daylighting

Daylighting studies have been undertaken and developed for many decades. Terms and methods used in this study field are specific and have been continually created and replaced. Some of them consequently become invalid or out of date and are longer used while some are not related to architectural design aspects.

1) Lighting terminology

The theory of lighting is consistent and can be applied to daylighting in general. The following terms were frequently used in previous research and will be in these studies.

a. Luminance L

Indicating brightness of a surface, luminance (L) is a physical measure of the luminous flux that passes through or is emitted or reflected in a given direction from unit area of a surface. It is an indicator of the brightness of a surface. As there are two type of luminous surfaces (self-luminant surfaces and transmitted or reflected surfaces), luminance value generally depends on light sources and either transmittance or reflectance of the surface that is influenced by the light. The SI unit of luminance is candela per square metre (cd/m^2).

b. Illuminance E, luminous flux F and lumen ∅

Illuminance (E) is the amount of luminous flux (F) incident upon a surface per unit surface area. The quantity of luminous flux (∅) called is measured in lumens (lm). It mainly indicates lighting performance in terms of quantity. Illuminance thresholds have been suggested as design guides to recommend the amount of illuminance required for specific types of task, space function or activity. The SI unit of luminous flux is the lumen (lm) and the SI unit of illuminance is the lux (lx).

c. Contrast

For lighting contrast is the luminance difference of two specific parts in the field of view. For example, those parts can be task and its background or focused task and adjacent surfaces. Contrast is valued as a proportion of them. Their relationship can be described by a formula:

$$\text{Contrast} = \frac{L_2 - L_1}{L_1} \qquad \text{(2.1)}$$

d. Daylight

'Daylight' is "the combination of diffused light from the sky and sunlight" (according to Baker and Steemers, 2002). 'Diffused daylight 'or 'skylight' stands for the light that has been scattered by particles in the Earth's atmosphere, such as air molecules and watery vapour of the clouds. 'Sunlight' is visible light which is a part of the direct beam of solar radiation. Daylighting systems have been applied for transmitting and redirecting natural light in to the inside spaces using building façade and fenestration and room surface as media. Side lighting provides natural light to room interior from windows. For top lighting, natural light enters through the top part of an interior space. While the application of side lighting is more flexible, top lighting provide better daylight distribution in term of quantity and quality.

e. Visual comfort

Visual comfort is the condition when people feel satisfied with the visual environment in a building. Good lighting quality leads to visual comfort but there are other influential factors, such as clarity of tasks and visual obstruction. Differently, the term 'discomfort' has been generally used for lighting aspect and associated with occurrence of glare. For daylighting studies, visual comfort has been found difficult to assess. The most effective assessing method is occupants' satisfaction survey but there might be errors due to the fact that peoples' feeling are subjective and contain many personal factors. The assessment of glare also can indicate discomfort but it has to be noted that it is visual discomfort in only lighting context.

f. Glare

'Glare' is a visual sensation produced by a visual field luminance that is substantial higher than the acceptable level of human eye adaptation. It has been recognized as an important factor of visual comfort (Rea, 2000). Main factors of glare consist of human eye adaptation, luminance of light sources, relationship between source position and occupants' line of sight and luminance of surface and sources in the field of view. Due to the fact that it is a sensation, it cannot be measured directly. Different levels of glare can cause annoyance, discomfort or loss visual performance and visibility. In terms of sensation level, it can be divided in to 'discomfort glare' and 'disability glare'. The occurrence of discomfort glare is usually distracting and irritating at the perceived time. Health problems such as eyestrain and headaches can occur when facing discomfort glare in long period. Disability glare occurs in the condition that intensive luminance of light source dominates overall luminance in field of view reducing visibility. For types of luminance source, it can be categorised to be direct, indirect, reflected and overhead glare. Direct glare causes by seeing light source directly while indirect and reflected glare are from secondary sources such as diffusing transmitted glazing and reflective surface. They can be either discomfort or disability glare whereas overhand glare is disability glare. Overhead glare or veiling reflection is caused by excessive reflected light on a visual task surface which is generally glossy leading to inability to see objects on the surface. Boubekri and Boyer (1992) illustrated evidence that people can tolerate glare from daylighting more than that from artificial light. Although various glare indicators have been raised for several decades, Boubekri and Boyer (1992) also pointed out that their ability to assess glare from daylighting is still being questioned. It is because of complexity of daylight sources. In addition, aesthetic of view from window probably affects assessment of glare.

2) Lighting standards and recommendations

According to previous research, there are a number of studies that focused on the practicality of lighting metrics and suggested some useful metrics. At the same time, diversified selections were subjectively made for each daylighting design research. The different indicators which have been used in those studies may result in difficulties in comparative studies but a more critical issue can be insufficient empirical proof obtained for the metrics and their recommendations. It is possible that the researchers used their familiar indicators meanwhile other metrics continually have been developing. In order to study the use of them in design application study, this review will focus on the metrics which were found as daylighting indicators consisting of illuminance, illuminance ratio, uniformity ratio, luminance, luminance ratios and other visual comfort indexes.

a. Horizontal illuminance at the working plane

The horizontal illuminance at the working plane is the simplest indicator of lighting quantity which has been used in lighting research in general. For classrooms, for example, Wu and Ng (2003) found that recommended horizontal illuminance levels for classrooms commenced in the UK in the 19th century and was set at 91 lux. The value tended increase with time (and lighting technology) until it reached a threshold of 300 lux in 1977 and appeared to be steady until the present time (see Tab.2.1 for more details). Classroom lighting standards have been recommended based on contrast of task and its environment, accuracy requirement, specific type of activity and occupied duration (Rea, 2000). According to the Illuminating Engineering Society of North America IESNA (Rea, 2000), higher illuminance levels are required when visual tasks have low contrast. The UK government's Building Bulletin 90 (DfEE, 1999) also suggests more illuminance threshold for detailed work. It is 300 lux for general activities and 500 lux for close or detailed work. For drawing spaces, higher lighting levels than general are definitely required. For more casual conditions, Baker (2000) suggested that less illuminance is needed. For newspaper reading, for instance, when reading concentration is not needed, only 50 lux is acceptable.

For general classrooms, illumination standards and recommendations have been suggested differently in various countries: 200-600 lux for UK and Europe, 300-500 lux for USA, 150-300 lux for India (ISI, 1975), 200 and 500 lux for Brazil (Zannin et al., 2008) and 300-500 lux for Israel (Boneh, 1982). For Thailand, the Illuminating Engineering Association of Thailand recommended 300-500 lux (TIEA, 2003) while at least 300 lux was enforced by Thai Building Control Act (RTG, 1994). However, those recommendations have been doubted for display screen equipment classroom, where less brightness is needed (Wu and Ng, 2003). Alrubaih et al. (2013) stated that requirements can be less than general standards for Information and Communication Technology (ICT) classroom. According to CIBSE: Code for Lighting (da Silva et al., 2012), 100-300 lux was suggested for computer base tasks (CIBSC, 2011) while IESNA recommenced 50-100 lux for seeing CRT screens (Rea, 2000).

According to a review by Alrubaih et al. (2013), less illuminance than recommendations is acceptable for a daylighting environment. For instance, The Education (School Premises) Regulations 1981 of

UK suggests a threshold of 300 Lux for daylit spaces but 350 lux for mixed use of daylight and artificial light (Wu and Ng, 2003). The National Research Council of Canada suggested at least 150 lux for the use of daylight. Additionally, the range of 108 to 5,400 lux was stated in LEED 2009 (USGBC, 2009).

People prefer a range of illuminance between 100 and 600 lux (Alrubaih et al., 2013). The differences in illuminance within the reference range depend on window facing position and distance, obstructions, influence of direct sun and amount of daylight. The upper illuminance below 1800 lux was rated acceptable. According to Altomonte (2009), approximately 1,500-2,000 lux was assumed to be the retinal illuminance threshold. These findings probably imply that there might be comfort range within the acceptable range. Differently, Piderit and Bodar (2012) applied 500-1,500 lux as a visual comfort criterion while suggesting 300 and 2,000 lux to be minimum and maximum values. The range of 300-700 lux was mentioned by Zannin et al.(2008) as the optimum range in the lighting software package RADIANCE. All in all, the whole range of all recommendations is 100-2,000 lux which is in agreement with the threshold of Useful Daylight Index (UDI) between 100-2,000 lux.

Interestingly, an illuminance threshold of 8,000 lux was suggested and can indicate the commencement of a direct sun influence (David et al., 2011). The value is much higher than upper recommendations in general. The results may reveal unacceptable high illuminances of sunlight but direct light was confirmed by many pieces of research (e.g.Boubekri and Boyer, 1992; Wu and Ng, 2003; Denan, 2004 and Varendorff and Garcia Hansen, 2012) as being acceptable in some circumstances.

Standards of illuminance alone obviously only indicate lighting quantity at a focused point which cannot represent room lighting environment because lighting distribution of the room contain variation of illuminance especially in daylighting environment. There are minimum, maximum and average values that may be able to show lighting performance of the room. Because of various daylight illuminances by room position and time changing, average illuminance has been applied representing room illuminance. Hunt (1979) pointed out that average illuminance may be a good indicator but minimum illuminance of the room can better indicate insufficiency light. Moreover, average value may not be practical for the conditions that highest and lowest light levels are significantly different because mean value will be too high to show insufficiency which too low to express excessive high lighting condition. Recently, calculation method such as Daylight Autonomy (DA) and Useful Daylight Index (UDI) has been introduced for solving daylight fluctuation problem.

Tab.2. 1 A summary of regulations and standards for classroom working plane illuminances

No.	Category	Illuminance (lux)	Code / Recommendation type	Year	For	Source
1	General recommendation	91	The London Building Acts	1894	UK	Wu and Ng (2003)
2	General recommendation	≥100	IES lighting code	1955	UK	
3	General recommendation	≥300	CIBS lighting code	1977	UK	
4.1	Daylighting	≥300	The Education (School Premises) Regulations	1981	UK	
4.2	Combination of daylight and artificial light	≥350				
5	General recommendation	≥300	CIBSE code for interior lighting	1984-1994	UK	
6	General recommendation	≥300	Guidelines for environmental design in school	1997	UK	
7.1	General teaching space	≥300	Building Bulletin 90: Lighting Design for Schools	1999	UK	DfEE (1999)
7.2	Teaching space with close and detail work	≥500				
8.1	Computer based tasks	100–300	CIBSE: Code for Lighting	2002	UK	da Silva et al. (2012)
8.2	Paper based tasks	200–600	Cen: EN 12464-1 Lighting of Work Places – Part 1: Indoor Work Places	2002	Europe	
8.3	Maximum values	1280–1800				
9	Classrooms/ Computer practice rooms	300	CIBSE Lighting Guide LG5: Lighting for Educational	2011	UK	CIBSE (2011)
10.1	CRT screen task	50-100	IESNA	2000	USA	Rea (2000)
10.2	Visual tasks of high contrast or large size	200–300-500				
10.3	Visual tasks of medium contrast or small size	500–750–1000				
10.4	Visual tasks of low contrast or large size	1000–1500–2000				
11	Daylighting	108-5,400	LEED 2009 for new construction and major renovations rating system	2009	USA	USGBC (2009)
12	Daylighting	≥150	National Research Council of Canada	N/A	Canada	Alrubaih et al. (2013)
13.1	Class desk top/ Chalk boards	150-300	Indian Standard Guide for Daylighting of Buildings	1975	India	ISI (1975)
13.2	Drawing and sewing	300				
14.1	Classroom desks,	300	Israel Standard (IS 889) for school lighting	N/A	Israel	Boneh (1982)
14.2	Drawing boards	500				
15	General recommendation	200-500	Brazilian Standard NBR 5413	N/A	Brazil	Zannin et al. (2008)
16	General recommendation	≥300	Ministerial Regulations No.39 B.E.2537(1994) by Building Control Act B.E.2522 (1979)	1994	Thailand	RTG (1994)
17.1	General studying area	300	TIEA-GD003 Thailand indoor illuminance recommendations	2003	Thailand	TIEA (2003)
17.2	Lecture room	500				
17.3	White board area	500				
17.4	Studio	750				
18.1	Too dark environment	<100	Useful Daylight Index: UDI	-	-	Nabil and Mardaljevic (2006)
18.2	Too bright environment	>2000				
19	Threshold values for retina	1,500-2,000	Research suggestion			Altomonte (2009)
20	Continue reading newspaper	50	Research suggestion	-	-	Baker (2000)
21.1	People preference	100-600	Literature review	-	-	Alrubaih et al. (2013)
21.2	Acceptable level	<1800				
22	Direct sun indicator	>8,000	Research suggestion	-	-	David et al. (2011)
23.1	Useful range	500-1,500	Research suggestion	-	-	Piderit and Bodar (2012)
23.2	Too dark environment	<300				
23.3	Too bright environment	>2,000				
24	Optimum rate of RADIANCE.	300-700	Research suggestion	-	-	Zannin et al. (2008)

b. Illuminance ratio

Illuminance ratio has usually been applied for display purposes and known as Display Illuminance Ratio (DIR) and exterior lighting design. In another approach, the Society of Light and Lighting recommended the use of illuminance ratio by introducing illuminance ratio chart for investigating effectiveness of room reflectance combination (SLL, 2003). For the ratio of horizontal working plane, the application is hardly found. The ratio consists of ratios of minimum and maximum illuminance, which is sometimes called *uniformity ratio*; and illuminance ratio of two visual tasks such as of surrounding and focused task. A summary of illuminance ratios is illustrated in Table 2.2.

Tab.2. 2 Recommendations of illuminance ratios for classrooms

No.	Ratio of	Index	Suggestion	Code / Recommendation type	Year	For	Source
1.1	E_{Min}/E_{Max}	Accepted	>0.5 (1:2)	Cen: EN 12464-1 Lighting of Work Places – Part 1: Indoor Work Places	2002	Europe	da Silva et al. (2012)
1.2		Recommended	>0.7 (1:1.43)				
2	$E_{Surround}/E_{Task}$	Recommended	0.2–0.8 (1:5-1:1.25)	CIBSE: Code for Lighting Cen: EN 12464-1 Lighting of Work Places – Part 1: Indoor Work Places	2002 2002	UK Europe	
3	E_{Min}/E_{Max}	Daylighting	1:5	SLL: Code for Lighting: Lighting Research and Technology'	2002	UK	Alrubaih et al. (2013)
4	between front and back of teaching spaces	Daylighting	1:3	Application of the D'Hautree School design	N/A	UK	Steemers (1994)
5.1	E_{Min}/E_{Max}	Non-critical areas	1:50	Personal recommendation	-	-	Apple (2008)
5.2		General working areas	1:20				
5.3		Critical areas	1:10				
5.4		Filming and television	1:3				

The ratio of surrounding illuminance and task were suggested at 0.2-0.8 in the UK and European standards (da Silva et al., 2012) while the D'Hautree School, a secondary school in Jersey, Channel Islands applied a ratio of 1:3 between front and back of teaching spaces for daylight distribution (Steemers, 1994). For minimum to maximum, Alrubaih et al. (2013) referred to the recommendation of the 'Code for Lighting: Lighting Research and Technology 2002' by The Society of Light and Lighting that 1:5 is suggested for the illuminance ratio horizontal working plane. Cen: EN 12464-1 'Lighting of Work Places' recommended the smaller ratio of more than 0.7, which is approximately 1:1.43, and suggested not more than 1:2 as an acceptable ratio. Conversely, Apple (2008) sugested a much higher range between 1:3 and 1:50 from most critical to non-critical areas.

Due to the fact that it is rarely applied, the practicality of illuminance ratio remains in question. The failure of any ratio is the levels of the two values can be either very high or very limit, therefore, it cannot indicate sufficiency of illuminance which is one of the most importance lighting assessments. More frequent application of similar ratio which is uniformity ratio implies less sensible of the ratio. Conflicts of recommendation in the review (shown in Table 2.2) also reveal weakness of this metric. In order to deal with illuminance ratio a new indicator, the vertical-to-horizontal illuminance ratio (VN ratio), was introduced (Love, 1990). However, there is no application found in daylighting design research.

c. Uniformity ratio

Uniformity ratio generally stands for the ratio of minimum to average horizontal illuminance on the working plane over the given area. The use of average illuminance leads to less errors from excessively high maximum illuminance. A uniformity ration of at least 0.8 is the general recommendation, which has been suggested for more than a decade, according to Building Bulletin 90 (DfEE, 1999) and BREEAM 2011 (BRE, 2011). However, the recommendation appears to be too strict when applied to daylighting design research. A study of a typical side-lit classroom in Taiwan (Chou et al., 2004), for example, found for a base case classroom that the ratio was 0.25-0.35 in summer and 0.13-0.76 in winter. When integrating a light shelf and artificial light, the ratio improved to 0.55-0.65 in summer and 0.51-0.63 in winter but was still lower than the standard. The researchers suggested an alternative acceptable ratio at 0.5, which was practical for their previous study (Chou, 1998). However, a classroom study in Chile (Piderit and Bodar, 2012) stated ratio of 0.7 as a visual comfort criterion, although they also applied a lower ratio of 0.6 as an acceptable threshold for the study. As can be seen in Table 2.3, the suggestions of Apple (2008) illustrated that a bigger ratio is required for more visually critical areas but the ratio appears too weak compared to other recommendations.

Tab.2. 3 Recommendations of uniformity ratio for classrooms

No.	Index	Suggestion	Code / Recommendation type	Year	For	Source
1	General task/ close and detail work	≥0.8	Building Bulletin 90: Lighting Design for Schools	1999	UK	DfEE (1999)
2	General space	≥0.4	BREEAM 2011 for New Construction: Non-domestic buildings	2011	UK	BRE (2011)
3.1	acceptable threshold	0.6	Research suggestion	-	-	Piderit and Bodar (2012)
3.2	visual comfort criteria	>0.7				
4	General space	0.5	Research suggestion	-	-	Chou (1998)
5.1	General working areas	1:10 (0.1)	Personal recommendation	-	-	Apple (2008)
5.2	Critical areas	1:5 (0.2)				
5.3	Filming and television	1:1.5 (0.67)				

According to suggestions from previous work, the sensible ratio might be in the range of 0.5-0.6 but it may need more evidence to confirm the practicality of the ratio.

d. Daylight Factor DF and Average Daylight Factor ADF

The Daylight Factor (DF) is the ratio between internal and external horizontal illuminance at the same time for overcast sky conditions. In percentage terms, the relationship can be illustrated as the formula:

$$\text{Daylight Factor (\%)} = \frac{\text{Indoor illuminance from daylight * 100}}{\text{Outdoor illuminance}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

The ratio was developed for overcast skies so the influence of direct sun is excluded. However, the impact of orientation was considered by combining an orientation factor. DF can be used as a daylighting metric as fluctuations in outside illuminance can be matched by changes in internal illuminance so that the perceived light level in a space appears steady. DF is a point-to-point value in a room, which is not an easy metric from a design point of view. The average daylight factor ADF attempts to convey a perception of the general daylight appearance across a whole room

Recommendations of DF and ADF depend on lighting type and difference of activities or tasks. Alrubaih et al. (2013) referred to the British Standards Institute (BS 8206 Part 2) that an ADF of 5% was suggested for a well daylit space while and ADF below 2% indicated artificial light would usually be required in daytime. Stein et al. (1992) suggested a lower DF for more casual activities while it is higher when detailed or long duration tasks are being undertaken. The range of ADF between 2%-5% was confirmed by many researches (see Table 2.4). Accordingly, a design implementation of the D'Hautree School also applied 5% of DF to be target with a minimum threshold of 2% (Steemers, 1994). None of the application suggested the ratio to be higher than 5%. An ADF greater than 5% was investigated and found to cause occupants' dissatisfaction and thermal problems (Alrubaih et al., 2013). However, some researchers, such as Li and Lam (2003) and BRE (2011) suggested or applied a minimum ADF threshold at values lower than 2%.

Additionally, some recent recommendations included percentage of floor area to comply with a certain levels of daylight factor in order to solve variations of illuminance distribution. While the UK rating system BREEAM suggested a 60-80% coverage (BRE, 2011) the Thailand rating system TREES stated that 45-55% of the room area should have adaylight factor of at least 2%.

Tab.2. 4 Recommendations of Daylight Factor for classrooms

No.	Category/ Task	Suggestion DF(%)	Areas to comply(%)	Code / Recommendation type	Year	For	Source
1	General recommendation	≥2	-	IES lighting code	1955	UK	Wu and Ng (2003)
2	Average for daylit space	4–5	-	Guidelines for environmental design in school	1997		
3.1	Ordinary seeing tasks, such as reading, filling, and easy office work	1.5–2.5	-	Recommendation from book: Mechanical and electrical equipment for buildings	1992	-	Stein et al. (1992)
3.2	Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work	2.5–4.0	-				
4.1	Average for daylit space	5	-	British Standards Institute: BS 8206 Part 2	2008	UK	Alrubaih et al. (2013)
4.2	Average for integration of daylight and artificial light	2	-				
5.1	preschool, school, further education	2	80	BREEAM 2011 for New Construction: Non-domestic buildings	2011	UK	BRE (2011)
5.2	higher education	2	60-80				
5.2	Minimum	0.8	-				
6	Minimum	2	45-55	Thai's Rating of Energy and Environmental Sustainability TREES-PRE NC Version1.1	2013	Thailand	TGBI (2013)
7.1	General recommendation	2%-5%	-	Research review			Alrubaih et al. (2013)
7.2	Dissatisfied threshold	>5	-				
8.1	Average	2	-	Research suggestion			Li and Lam (2003)
8.2	Minimum	0.6	-				
9.1	Average	5	-	Application of the D'Hautree School design	N/A	UK	Steemers (1994)
9.2	Minimum	2	-				

The daylight factor has been widely applied, but as a daylighting indicator it has limitations. It is practical for overcast skies which dense clouds and no direct sun. However, it has been questioned that it may not represent all daylighting cases because direct sun influences most of sky conditions and the daylight factor can vary dependent on the effect of the direct sun (Alrubaih et al., 2013). Hunt (1979) stated that to analyse illumination levels for any sky conditions which contains the effect of direct sun is complicated. As the main indicator, the daylight factor method was found to underestimate daylight in sunny sky conditions. Similarly, DF was refuted by David et al. (2011) due to the fact that it is unable to indicate daylight levels in general. They believed that this method was appropriate only for temperate climates where the sun has a low altitude. Recently, Cantin and Dubois (2011) suggested tha DF should be replaced by the useful illuminance index UDI, which is defined as the annual occurrence of illuminances across the work-plane that is within a range considered "useful" by occupants – 100 to 3000 lux. Although DF has been continually developed, its impracticality for other sky conditions cannot be denied. In other words, DF should not be applied to tropical areas where the sun influences the sky mostly whereas an idea of UDI is probably practical.

e. Luminance and Luminance ratios

Values of luminance are normally concerned with vertical tasks within eye level. Altomonte (2009) affirmed the significance of the vertical luminance distribution on visual comfort. Window luminance was found to be the best single indicator for operating blinds (Inkarojrit, 2005). The CEN: EN 14501 Blinds and Shutters standard suggested 4000–6000 cd/m^2 as a maximum window luminance.

For luminance ratios most researchers agree a 1:3 ratio for task to adjacent surroundings and 1:10 for task to more remotes surrounding (e.g CIBSE, 1994 and IESNA, 2000). It is sensible that low contrast is required within a 60°cone of view. For other angles higher ratios at 20:1 and 40:1 were suggested for contrast of luminaries to adjacent surfaces and anywhere in the field of view (CIBSC, 1994).

Tab.2. 5 Recommendations of luminance and luminance ratio for classrooms

No.	Value/ Ratio of		Suggestion	Code / Recommendation type	Year	For	Source
1	Maximum Window luminance		4000–6000 cd/m^2	CEN: EN 14501 Blinds and Shutters – Thermal and Visual Comfort – Performance Characteristics and Classification	2005	Europe	da Silva et al. (2012)
2	$L_{Paper}/L_{Surround}$		0.33–3 (1:3.03-3:1)	CIBSE: Code for Lighting	2002	UK	
3.1	Between the task and the adjacent surroundings		1:3	CIBSE code for interior lighting	1994	UK	CIBSE (1994)
3.2	Between the task and more remote lighter surfaces		1:10				
3.3	Between luminaries and the surfaces adjacent to them		20:1				
3.4	Anywhere within the normal field of view		40:1				
4.1	Between tasks and adjacent surface (for both paper of screen base)		1:3 or 3:1	Lighting Handbook: Reference and application volume	2000	USA	IESNA (2000)
4.2	Between tasks and non-adjacent surfaces at		1:10 or 10:1				
5.1	Between main visual task and in a cone of 60° and in a cone of 120° from the line of sight	Recommended	1:3:10	Research review	-	-	Cantin and Dubois (2011)
5.2		Acceptable (include window in view)	1:6:20	Research suggestion			
5.3		Tolerance (include small window in view)	1:N/A:50				

Although there is no conflict between recommendation, the ability to indicate lighting quality was doubted. Cantin and Dubois (2011) said that the ratios of 1:3 and 1:10 were too strict for daylighting and suggested ratios of 1:6 and 1:20 to be acceptable thresholds of the ratios when windows were located in the field of view. Cantin and Dubois (2011) report that the ratio of 1:50 can be tolerated when a small portion of a window is in the field of view. However, the suggestions was not strongly confirmed by the researchers as being appropriate to assess daylighting design.

For ICT classrooms, Ramasoot and Fotios (2009) also found that luminaire luminance guidance might be out of date and not accommodate accelerate development of technology. The guidance was rated too strict as higher luminance was tolerated for DSE screens. This reveals necessity of standard revises prior to applying to the study.

f. Visual comfort index

In order to improve daylighting design, previous research attempted to assess quantity and quality of the lighting environment. However, most studies reported results mainly in daylight distribution in the focused areas. Less of them can actually assess visual comfort. Visual comfort assessment has been developed with many metrics (summary of them shown in Table 2.6). Vertical luminance, like window luminance, has been applied to predict the possibility of discomfort. More than 4000–6000 cd/m^2 of window luminance can be higher than an occupants' acceptability, causing blind occlusion (CEN, 2005). Although Inkarojrit (2005) affirmed that it is indicative but it cannot directly indicate visual discomfort. Visual Comfort Probability (VCP) is the early index for assessing visual comfort of indoor lighting environments for artificial light. It is the percentage that occupants rate a given lighting condition comfortable (da Silva et al., 2012). Values of more than 70 and 80% were recommended by IESNA (Rea, 2000). It may have been suggested recently, but lack of implementation was found in daylighting design research. Sensibly, the index can be impractical because it was developed for artificial light condition.

Glare is one of the main indicators that can signify discomfort conditions. Unified Glare Rating (UGR), Daylight Glare Index (DGI), and Daylight Glare Probability (DGP) were the indices used as visual discomfort indicators. UGR is a simple calculation for indicating glare. As a less complicated procedure, the consensus is that it can ultimately replace VCP. CIBSE's Code for Lighting and CEN: EN 12464-1 Lighting of Work Places recommends a maximum UGR at 19, with more than 22 standing for uncomfortable conditions (da Silva et al., 2012). A standard in Thailand suggested a UGR of 19 and 16 for learning spaces and lecture room and studios respectively (TIEA, 2003). It reveals that more detailed visual work needs a lower UGR. However, since the index is based on electric lighting, it may not be practical for daylighting condition.

DGI is a metric for assessing daylighting. The main difficulty of daylit spaces is discomfort glare, with direct sun being a significant factor. The index is calculates from average window luminance, the solid angle, average luminance of the field of view and the position index. Four formulae and a computer program such as EnergyPlus are required to examine DGI. Suggested levels of index can be seen in Table 2.7. DGI values between 16 and 22 appear to be acceptable, while the range of 22-28 is tolerable. When comparing to IES Glare Index (GI) which is for artificial lighting, tolerance levels are the same while the acceptable range is larger at 10-22. It implies that assessment of glare in daylighting space is more flexible than an artificial lighting environment. DGI recommendations for learning spaces with and without computer tasks are 16 and 19 respectively. The New Daylighting Glare Index (DGI_N) method was introduced to improve DGI accuracy

(Nazzal, 2000). The method contains standard monitoring protocols and calculations of improved factors: window, adaptation and exterior luminance; the solid angles and configuration factor of the window. More factors were considered for DGI_N particularly with the addition of outdoor factors. The index has proved more accurate than DGI but the researcher who developed this index suggested more validation was needed to confirm its practicality. Whether DGI or DGI_N has been questioned in terms of compatibility for different daylighting sources. Boubekri and Boyer (1992) found that perceived glare under sunny sky conditions appeared to be more tolerable than DGI. The result implies that DGI may be too strict for daylighting condition, especially with the impact of direct sun. According to Alrubaih et al. (2013), the index appears to overestimate for non-uniform window luminance. Many occurrences of discomfort glare were much lower than the threshold of 22. These findings imply that the range of DGI tolerance level is larger than the recommendations for the sky that involves the direct sun.

DGP is the a metric for analysing glare that require application of virtual cameras with a 180° fish eye lens and DGP computing program (Wienold and Christoffersen, 2006). It was applied with percentage of area of external view and affected the frequency of direct sunlight to examine the effectiveness of different types of façade designs. The main factors consisted of vertical eye illuminance, the glare sources luminance, the solid angle and the position index. Varendorff and Garcia Hansen (2012) said it could solve the complexities of glare assessment, especially for large light sources. It was rated to more correlate to discomfort glare compared to other metrics because of its strong dependency on vertical eye illuminance, which has associated with visual comfort. For this reason, it appears that DGP can be successfully used to assess the visual environment. However, the value was found to be weaker than the perceived glare sensation. The result showed that the more direct sun influences the scene then the worse the DGP; however, the least impact of direct sun was not the best case. Accordingly, Yun et al. (2014) pointed out that much effort was required to apply the calculation. Instead of DGP, maximum vertical illuminance at eye level at 3,000 lux was suggested. The value was stated as corresponding to a DGP of 0.4, which stand for the threshold of disturbing glare.

Chaiwiwatworakul et al. (2009) state that visual glare assessment was never included in previous façade design studies. It might be due to the fact that glare assessing procedures are either too complicated or incompatible for daylighting. When previous research was reviewed, most of indicators have been found to be too complicated. Simplified versions of them have been continuously suggested. Apart from suggestion of vertical illuminance at eye level (Yun et al., 2014), Torres and Sakamoto (2007) applied simplified daylight coefficient and DGP. Only eye level vertical illuminance was considered in the suggested DGP. However, a large number of formulae and technical methods were still needed to achieve the assessment.

Tab.2. 6 Summary of glare indexes

Index	Method/ factors	Objective, advantage	Limitation	Source
Maximum window luminance	Observation	- Simple method - Indicative	May be able to predict blind operation but cannot directly indicate visual discomfort	(Platzer, 2003), (CEN, 2005)
Visual Comfort Probability (VCP)	The percentage that occupants rate a given lighting condition comfortable	For assessing visual comfort of indoor lighting environment for artificial light	Based on electric lighting.	(Guth, 1966)
Unified Glare Rating (UGR)	Calculation system	- Simple calculation procedure than VCP - Can ultimately replace VCP - Consensus	Based on electric lighting.	the International Commission on illumination (CIE)
Daylight Glare Index (DGI)	- Calculation system/ computing program - Factors: average window luminance, the solid angle, average luminance of the field of view and the position index	Indicate the degree of daylight discomfort glare for non-uniform window luminance	- Probably overestimated - Still being developed	(Fisekis et al., 2003), (Osterhaus, 2005), (Bellia et al., 2008)
New Daylight Glare Index (DGI_N)	- Calculation system - Factors: window, adaptation and exterior luminance; the solid angles and configuration factor of the window	Increase accuracy of DGI	Has not been validated with other studies.	(Nazzal, 2000), (Nazzal, 2001), (Nazzal, 2005)
Daylight Glare Probability (DGP)	- percentage that occupants face glare in a given visual condition - Calculation system/ computing program/ measurement - Factors: vertical eye illuminance, the glare sources luminance, the solid angle and the position index	- better correlation to discomfort glare comparing to other metrics - strong dependency on vertical eye illuminance - overcome the difficulty of glare prediction from large sources	Complicated	(Wienold and Christoffersen, 2006)

Various indicative methods such as DA and UDI can improve the value more practical for solving daylight fluctuation. Cantin and Dubois (2011)'s findings indicated UDI and DGP as the useful metrics for daylighting study. For lighting quality, uniformity ratio, daylight factor, luminance ratio and glare index like DGI and DGP are frequently utilised although they are doubted for practicality in all circumstances. Some of these indicators were found complicate, therefore, researchers rather applied other simple metrics despite the fact that limitations of them were accepted. Some new indicators were introduced but use of them is rare. CHPS (2006), for instance, combined daylight factor with direct sunlight penetration and recommendation of 400-4,000 lux of Daylight Saturation Percentage (DSP) for investigating lighting energy saving. In addition, vertical luminance and illuminance which strongly related normal field of view is fairly acceptable to indicate visual comfort

Tab.2. 7 Recommendations of glare indexes

No.	Index	Category	Suggestion	Code / Recommendation type	Year	For	Source
1.1	VCP	Recommended value	>70	IESNA recommendation	2000	USA	(Rea, 2000)
1.2		Minimizing discomfort glare	>80				
2.1	UGR	maximum (offices)	19	CIBSE: Code for Lighting	2002	UK	da Silva et al. (2012)
2.2		uncomfortable	>22	Cen: EN 12464-1 Lighting of Work Places – Part 1: Indoor Work Places	2002	Europe	
3.1	UGR	General studying area / Lecture room/ White board area	19	TIEA-GD003 Thailand indoor illuminance recommendations	2003	Thailand	TIEA (2003)
3.2		Studio	16				
4	GI	Just intolerable	28	IES lighting code	1973-1977	UK	(Chauvel et al., 1982)
		Uncomfortable	25				
		Just uncomfortable	22				
		Acceptable	19				
		Just acceptable	16				
		Noticeable	13				
		Just perceptible	10				
5	GI	General teaching space/ close and detail work	19	Building Bulletin 90: Lighting Design for Schools	1999	UK	DfEE (1999)
6.1	GI	Classrooms	19	CIBSE Lighting Guide LG5: Lighting for Educational	2011	UK	CIBSE (2011)
6.2		Computer practice rooms	16				
7	DGI	Just intolerable	28	Research recommendation			(Chauvel et al., 1982)
		Uncomfortable	26				
		Just uncomfortable	24				
		Acceptable	22				
		Just acceptable	20				
		Noticeable	18				
		Just perceptible	16				
8	DGI	uncomfortable	24–26	Research recommendation			(Fisekis et al., 2003)
		comfortable	≤22				
9	DGP	intolerable	≥28	Research recommendation			(Wienold and Christoffersen, 2006), (Wienold, 2009)
		imperceptible	≤0.35				
		perceptible	≤0.40				
		disturbing	≤0.45				

3) Daylighting method

From previous research three methods were found that have been applied for analysing daylighting performance in architectural designs. There are calculations, physical models and computer simulation techniques. According to the study by Aghemo et al. (2008) simulation technique and scale model measurements are the methods that architects generally use in their design stage. It reveals that either a technique like calculation method may be too complicated for architects or it was found too specific to apply to other design contexts. However, for researchers the three methods remain the technique which has been selected for investigating performance of daylighting design in different circumstances.

a. Calculation method

Daylighting calculation has been used for analysing daylighting performance in focused spaces. Three calculation methods - Lumen Method, Average Daylight Factor and Daylight Autonomy (DA) - were introduced. According to previous research, only the Lumen Method and Daylight Autonomy were found to be used as the main method.

Lumen method is a calculation method used for examining horizontal illuminance on a general working plane. The method is practical for side lighting from window, including the influence of light from the sky and ground reflections. According to IES (1989), the common formula is:

$$E = T_e\,(E_{xvk}CU_k + E_{xvg}CU_g) \quad \text{...} \quad (2.3)$$

where E = interior illuminance on horizontal working plane

T_e = transmittance of the window

E_{xvk} = exterior vertical illuminance from the sky

CU_k = coefficient of utilization from sky luminance

E_{xvg} = exterior vertical illuminance from the ground

CU_g = coefficient of utilization from the ground.

In order to determine the exterior vertical illuminance from the sky, the exterior horizontal illuminance is required for both diffused light from the sky and direct sunlight. In addition, the view factor and additional illuminance of reflections from shading devices and surroundings have to be included. Studies in Thailand (Chirarattananon et al., 1996; Chungloo et al., 2001a; Chungloo et al., 2001b), applied the method in their studies by integrating with the DOE-2 computing program and other calculations like OTTV for energy conservation aspects. Using the lumen method, Chirarattananon et al. (1996) found that the method generally overestimated exterior illuminance from the sky while underestimating illuminance from the ground compared to measured data. However, the total predictions appeared no greater than 40 lux above measured data. Moreover, Chirarattananon et al. (1996) raised some evidence in cities in the tropics that when the Lumen Method was applied, interior illuminance was generally sufficient only when shading devices were excluded. Inadequate illuminance when shading devices were combined may be proved but not in every circumstance. Many pieces of research using other methods, such as Chou et al. (2004) and Ho et al. (2008), could confirm the sufficiency of daylight when some kinds of shading device were added. Consequently, it questionable whether the Lumen Method is practical for applying in hot climate areas where solar shading is necessary.

Average daylight factor calculation can provide overall daylight level in focusing area. Due to façade factors included, calculated result of design alternatives can simply be compared. The calculation is based on a theoretical overcast sky. Average daylighting factor from window can be predicted using formula (DfEE, 1999 and SLL, 2014):

$$\text{Average Daylight Factor} = \frac{T A_W \theta M}{A (1- R^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4)$$

where T = glazing transmittance

A_w = glazing area

θ = window sky acceptance angle

M = maintenance factor

A = total room surface area

R = area-weighted average reflectance

Similar to the Lumen Method, the average daylight factor was found useful at the very early stages of a design. The calculation provides only an average value but appear not practical for acquiring daylight distribution. Moreover, the method is applicable only for diffuse skies does not include the effect of sunlight.

Daylight Autonomy (DA) as well as *Useful Daylight Illuminance (UDI)* was recently introduced known as climate based daylight modelling. The methods are developed for assessing daylighting calculation by including a time element. DA is the percentage of the time that daylight level reach illuminance threshold. It can be annually, seasonal, monthly or daily. David et al (2011) endorsed DA as a suitable method for tropical climates. The estimation requires average daylight factor, availability data of diffuse horizontal daylight and orientation factor. UDI is the annual occurrence of working plane illuminances that was considered useful. Using similar calculation method, the UDI was suggested by Nabil and Mardaljevic (2006) using the ratio of time that illuminances are in the range of less than 100 lux and more than 2,000 lux which represent too dark and too bright conditions. The recommended ratio that can show sufficiency of illuminance is 50% of time of the year. These two indicators become important in research that obtain in the area that direct sun influence mostly on ambeint daylight. Due to their advantages, the use of methods tend to increase. However, DA may be becoming an IESNA recommend metric, but the methods are not included in any standards for guidelines. SLL (2014) stated that their practicality is being questioned.

b. Physical model

For analysing daylighting quantity, the distribution of illuminance levels on the horizontal working plane and vertical luminance of task are measured in spaces using illuminance and luminance meters. Basically, the space photos are applied for investigating lighting quality. Equipment like virtual cameras with a 180° fish eye lens is integrated with computing program to assess glare level. Two main objectives of the method consist of a design development aid in preliminary stages and post construction assessment. For field measurements actual building data can be obtained using this method either for assessing lighting performance of the environmental design or collecting empirical data for simulation technique validation. The full-scale building is rarely used for design alternative study because changes of building or room element are costly and laborious. Scale models were r introduced to solve those issues. The method provides an opportunity to examine real building materials and large numbers of design solutions, particularly for some certain elements such as orientation. Many ranges of scale havebeen selected for various purposes. For analysing daylight, the model is usually built at a scale from 1:10-1:100 (SLL, 2014). For declaring practicality of the scale down method, Aghemo et al. (2008) demonstrated evidence that the scale of models does not make a significant difference to the actual building for daylighting study. However, it still costly and time consuming, particularly when the model is complicated or more details are required. Moreover, the size of some innovative material, such as prismatic glazing, may not be able to be scaled down accurately to be the same scale of the models.

The physical model technique can be obtained either using an actual sky or artificial skies such as a mirror box and hemispherical sky dome (SLL, 2014). The data collection from real sky appears the most realistic and reliable. Sky condition can be the same as the research site, but fluctuation of the daylight may cause problems in terms of comparative study. The collected results can be converted to be ratios such as daylight factor and comparable but still have limitations. The appearance of ambient illumination is unique for each sky condition at any specific time and day due to sun geometry and amount of cloud. Repetition and comparison of measurements can be questioned.

A *Heliodon* is an artificial sun geometry system consisted of an adjustable spotlight with tilting and rotating table. The device is used for studying effect of direct sun penetration and building shadow that develop in a range of time and season. Sky conditions are not included in this device. The *Mirror Box* is a sky simulator that contains a luminous ceiling and mirror walls. The device is illuminated by several fluorescent lamps representing the illumination from an overcast sky. Obviously, the effect of the sun is excluded for the sky. The *Hemispherical sky dome* is the technique by which the daylighting from the sky and the sun are integrated. The illuminating dome covering the space stands for effect of overcast sky. The reflective surface of the dome was designed to be illuminated along dome perimeter. An adjustable spotlight or scanning sky simulators work as the sun (Aghemo et al., 2008). Unlike real skies, under an artificial sky not only can two daylighting sources be integrated but also the analysis can be repeated by just selecting the same sky condition. The disadvantages are that a reliable sky construction by experts is required and there is a high budget. For accessing a system additional cost and time will be made. Additionally, although the sky condition which contain the lowest average illuminance such as overcast sky was suggested for assessing sufficiency of illumination levels (Steemers, 1994), artificial skies are doubted by many researches that it may not be able to represent other sky conditions (Aghemo et al., 2008). Furthermore, the research outcomes from artificial sky result in some errors. For example, Supansomboon (2001) found that diffused condition of a sky dome was not compatible for side lighting as luminance at the horizontal line of the dome surface where luminaire located was much higher than average. The brightness pattern proved different to real sky. Accordingly, undesirable reflections of luminaires and errors from horizontal line were raised by Aghemo et al. (2008) that is the main problem of sky scanning simulators.

The research that used this technique as the main method is tending to decline. The method appears to be replaced by computer simulation technique. A lack of study in this method may result from the unavailability of equipment. There is some research studying at places that still have an artificial sky available. Aghemo et al. (2008), for example, applied their study in a sky scanning simulator at the Daylighting Laboratory of the Politecnico di Torino, Italy.

c. Computer simulation

Computer simulation is becoming a more frequently use methods for daylighting analysis. The analysis requires many light level points to be displayed and many cases in different times and seasons to be acquired. It consequently is the most appropriate tool available for dealing with those difficulties. While calculation and measurement was assigned for analysing lighting environment in many sustainable rating systems such as BREEAM (BRE, 2011), LEED (USGBC, 2009) and TREES (TGBI, 2013) simulation techniques were suggested to be used, with no specific program. Various computing packages have been applied to previous studies generally with measurement validation. Lumen Micro, AGI32, RADIANCE, Lightscape, SPOT and DAYSIM were suggested to be reliable computing programs for predicting daylighting and direct sun penetration in design criteria of high performance school used in California (CHPS, 2006). However, not all of the suggested programs are compatible for daylighting analysis. For assessing daylighting design performance, Ecotect, RADIANCE and DAYSIM have been generally applied for many pieces of research. The programs have differences in terms of function.

Ecotect or Autodesk Ecotect Analysis is a sustainable building design software for facilitating decision making at the very earliest stages of design when the greatest impact on the overall performance of a project can be made. Therefore, the main target group of program development is architects. The designers were aimed to use the software themselves because it is them who know fundamental criteria and physical phenomenon the most. The main parameters that the program focuses on consist of acoustic design, climate analysis, human comfort, psychometrics, thermal analysis, passive design, shading design and lighting design. According to previous research, Ecotect was applied for studies including energy demand (Muhaisen and Dabboor, 2015) and illuminance improvement and heat protection (Perez et al., 2012). Although some of the results were report as sensible, Perez et al. (2012) revealed uncertainties by suggesting RADIANCE as a more accurate device. It implies limitations of the daylighting analysis function in Ecotect.

Radiance is a program that is generally applied for the analysis and visualization of lighting design in terms of quantity and quality. Apart from artificial lighting, daylighting calculation is also available. Calculated outputs consist of luminance, illuminance and glare indices. Results can be displayed as numerical values, coloured images and contour graphs. As for limitations, the developer stated that some types of geometry and materials may not be able to be simulated. As a program user, Denan (2004) pointed out that glare calculation from this technique might be impractical for daylight condition in Malaysia since conflicts between RADIANCE and their survey occurred. In addition, the software was said to be not practical for presenting variety of result in each time (Yun et al., 2014)

DAYSIM is a daylighting analysis software based on RADIANCE. The software can predict annual Illuminance using daylighting metrics: DA and UDI. For daylighting quality, annual DGP prediction was included. Electric lighting energy also can be estimated. The program allows alternatives of occupancy schedule, shading and lighting operation systems. Although it does not support thermal aspects, it approaches integration for energy simulation programs such as EnergyPlus, eQuest and TRNSYS.

Accepting their limitation, some researchers applied the program alone such as Muhaisen and Dabboor (2015) and Perez et al. (2012) using Ecotect. RADIANCE was used by David et al., (2011) and Torres and Sakamoto (2007), and Rupp and Ghisi (2012) applyed DAYSIM. Most studies combined one with another. Because of the limitations of the daylighting analysis in Ecotect and the unavailability of thermal aspects in RADIANCE, RADIANCE and Ecotect have been widely integrated with other software into many other studies (e.g. Denan, 2004; Zannin et al., 2008; Varendorff and Garcia Hansen, 2012 and Le Hong and Rodriques, 2013). Instead of Ecotect, Revit or EnergyPlus sometimes were used with RADIANCE (e.g.Kim and Kim, 2010; David et al., 2011; da Silva et al., 2012 and Yun et al., 2014). There are some researches that included DAYSIM but all of them also applied RADIANCE as the main illumination simulating technique

(Carew and Mpauli, 2012; David et al., 2011; da Silva et al., 2012 and Yun et al., 2014 for instance). The combination of the softwares appears insufficient when researcher also applied other additional programs. For example, Grasshopper and Rhino were applied with Ecotect for better graphic modelling (Varendorff and Garcia Hansen, 2012) while Rhino can provide dynamic simulation of DGP which a combination of RADIANCE and DAYSIM cannot (Yun et al., 2014). Yun et al. (2014) claimed that importing lighting schedule data from Rhino was more accurate than using EnergyPlus alone.

For daylighting design purposes some other programs have been used in research. DIAlux (Saihong and Srisutapan, 2007 and Intarakulchai, 2013), Lightscape (Wong and Khoo, 2003 and Wong et al., 2004) and ray tracing and Radiosity algorithms (Chou et al., 2004). The users of lighting programs in design and research are faced with issues of complexity in daylighting analysis. The two main weaknesses of lighting simulation programs relate to simulation speed and computational accuracy. For example, Kjeil, 2014 pointed out that reflections are one of complicated issues for lighting simulation since most software only allow a limited number of 'bounces' or reflections to be calculated, thereby reducing the accuracy of the simulation. Many previous studies have examined lighting simulation packages. Wong (2017) compared lighting simulation programs from previous studies and reported that RADIANCE was the most widely utilized and most highly rated lighting software (in terms of accuracy and practicality for most types of complicated design). RADIANCE-based studies include Mardaljevic, 1995; Ubbelohde and Humann, 1998; Wang and Zhai, 2016. RADIANCE also provides the most accurate and realistic lighting simulation results for complicated designs and multiple reflections of interior spaces. However, apart from the fact that expertise is needed for using the program, RADIANCE has also been confirmed to have limitations, such as less accuracy in predicting the cases that were influenced by direct sun. Tian et.al. (2001) point out that RADIANCE is not appropriate in long-term simulation, especially for predicting complicated models such as windows with venetian blinds. Furthermore, although RADIANCE's open source licence of the software was announced in 2002 to encourage further development and distribution to the public, other software packages have been developed that have more user-friendly interfaces than RADIANCE. For early-design stage, easy-to-use tools that were based on RADIANCE software such as Daylight 1-2-3 (Reinhart et.al., 2007) and DesignBuilder (Kirimtat et.al., 2016) have been suggested.

.Christakou et.al. (2005) concluded in 2005 that there is no ideal daylighting simulation package available. Users were suggested to deal with existing software with expertise. Combination of programs has been applied integrating strengths of software. Apart from accuracy of the simulation results, Christakou et.al.

(2005) suggest that the programs should have a user-friendly interface. RADIANCE, DESKTOP RADIANCE and RAYFRONT were concluded too difficult to be applied in design stage while RELUX and Lightscape are user friendly. Lightscape may be available for selecting various sky conditions, including or excluding direct sun, but Wong and Khoo (2003) stated that the integration of daylighting and artificial light was still one of the program's limitations. Apart from the fact that Lightscape discontinued service since 2003 (Kirimtat et.al., 2016), lack of precision was affirmed as the main weakness of Lightscape (Ubbelohde and Humann, 1998 and Christakou et.al., 2005; Acosta et.al., 2015). According to in-depth analysis of Acosta et.al. (2015), 3DS Max, Daylight Visualizer, DAYSIM and DIALux other user-friendly software were found having considerable low relative different to analytical calculation while more error margin was found in DesignBuilder at near window positions. The result also illustrates that DesignBuilder can precisely calculated in general.

DIALux is free software broadly applied for facilitating lighting design with different national standard (Acosta et.al., 2015). An increasing number of published works applying DIALux for indoor and outdoor from 2005 to 2015 (Mangkuto, 2016). The fact that its ability to calculate light exchange between light source and illuminated surface with dynamic lighting conditions, the program can also applied for indoor and outdoor daylighting estimation and provides acceptable results. Apart from it is for free, the key advantages of the device can be the software is user-friendly and up to date. The user can simply model the building while the program is also compatible with other architectural drawing programs. DIALux software has been updated improving lighting calculation and data of luminaires. While it is well known as a useful device for lighting design, its reliability for daylighting analysis is also confirmed by Fakra et. al. (2008). Mangkuto (2016) confirms that the program works with high accuracy for calculation point light source, diffuse reflection and interreflection but, similar to other software, inaccuracy can be found in calculation of sky and external reflection.

For thermal and energy aspects, apart from using Ecotect, EnergyPlus, eQuest and TRNSYS, DesignBuilder was also considered. The program again required integration of others. Martinez et al. (2012), for example, included DesignBuilder for analysing a double skin façade which eQuest and EnergyPlus cannot. When all the programs used from previous studies were considered, there are Ecotect and DesignBuilder that provide not only energy and thermal simulation but also daylighting analysis. The capacity of daylighting analysis in Ecotect appears to be limited specially for different sky conditions, change of time and season while no application of daylighting analysis in DesignBuilder has been published.

DesignBuilder is another design tool aims to be user friendly software that allows architect to import model form drawing programs such as AutoCAD, optimise their design in every stage and link data with BIM. The key indicators consist of energy consumption, carbon emissions, thermal comfort, daylighting level and cost. The program simplified thermal simulation from EnergyPlus and daylighting analysis from RADIANCE. The daylighting analysis is the new function that is being developed. Different to Ecotect, the tool allows alternatives of sky conditions and specific dates and hours. According to the review of Jakica (2018), DesignBuilder may have less functionality for lighting simulation than RADIANCE but it can model lighting to a good standard of accuracy.

In order to use simulation techniques, apart from high performance computer and specific expertise needs, the software itself results in difficulties. While highly reliable programs are complicated, user friendly packages have many limitations and need additional methods to fill the gap. Combinations of many tools can also cause complexity. This complexity can be one of the reasons that some researchers stepped back to apply some former manual method, such as Le Hong and Rodriques (2013) using stereographic diagram with shadow masks for studying sun penetration (Perez et al., 2012) and the Light-Thermal method (LT) for energy consumption for analysing lighting, heating and ventilation (Le Hong and Rodriques, 2013); with simulation technique.

In order to assess design strategy performance, the daylight modelling techniques were applied at the design stage. Computer programs are very useful for facilitating detailed selection at the design stage, especially for complicated design project but many input data, high specification computer and computer skills are required for this method. Because differences in weather conditions generally bring about diverse daylighting results, daylight data are compulsory for all techniques (Steemers, 1994). The next section describes the climate of Thailand, the country in which this study is based.

2.2 Tropical climate in Thailand

Figure 2.1 shows the main climatic zones of Earth. In general, there are Tropical, Temperate and Cold climates for the north and the south hemispheres. The areas at and either side of the Equator are in the Equatorial and Subtropical climates due to their distinct characteristics. The climates can be further categorised to be other climate areas depending on specific topography such as Desert, Marin west coast. The tropical zone stands for the areas from latitudes of 10ºN to 23°27'N and 10ºS to 23°27'S, known as the Tropic of Cancer and Tropic of Capricorn. The tropical climates contain a longer dry season during the winter than Equatorial zone while they are influenced by solar radiation more than subtropical climates in average. The length of strong solar radiation is typically about eight hour per day (Edmonds and Greenup, 2002). Different to temperate zones, the length of day time between summer and winter are approximately equal. Each area in tropical zones contains different combinations of dry, humid and wet. In different length, they generally consist of summer and winter. The summer includes rainy seasons while the winter is generally dry. In this part, specific climate of Thailand will be presented

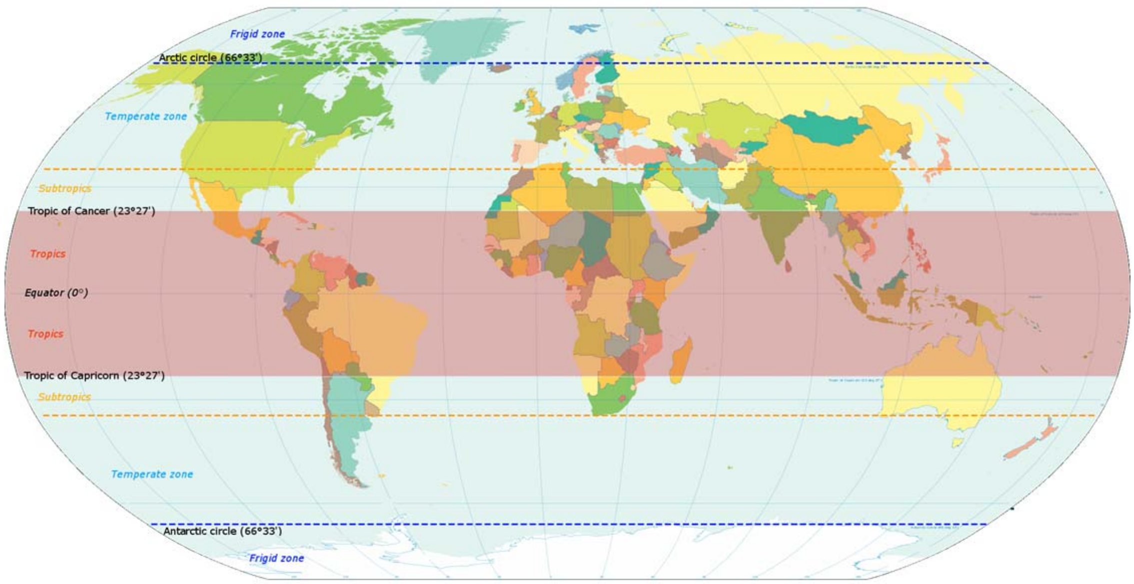


Fig.2. 1 World map show climate - regions divided by world latitudes.

Source: KVDP (2013)

Thailand is located between latitudes 5º37'N to 20º27'N and longitudes 97º22'E to 105º37'E. The boundaries of Thailand are adjacent other countries in the north and the sea of the Gulf of Thailand in the south (Figure 2.2). The area has a hot humid climate because it is under the influence of monsoon winds and other factors such as Inter Tropical Convergence Zone (ITCZ) and tropical cyclones (according to Thai Meteorological Department). The main monsoon winds are southwest monsoon and northeast monsoon. Stream of warm moist air from Indian Ocean is delivered by the southwest monsoon resulting in plenty of rain to the country. The anticyclone on the China mainland lead to the northeast monsoon containing cold and dry air provide coldness for major parts particularly in the north and the northeast. From a meteorological aspect, Thailand can be divided in to three seasons: winter, summer and rainy seasons. Under the influence of the northwest monsoon, mid-October to mid-February represents winter period. Rather than cold, the weather is actually mild in most areas. Minimum and maximum temperature based on the 1971-2000 period are 17.1ºC and 31.9ºC on average (TMD, 2012b). The coldest period is during December and January. Summer is approximately during mid-February to mid-May when the area is often experiencing the northeast monsoon and before the coming of the southwest monsoon. Summer temperatures are on average between 21.4ºC and 35.8ºC. The hottest days with maximum temperatures over 40ºC are usually at the end of April. Southwest monsoon or rainy season is usually during mid-May to mid-October. Abundant rain usually occurs from August to September.

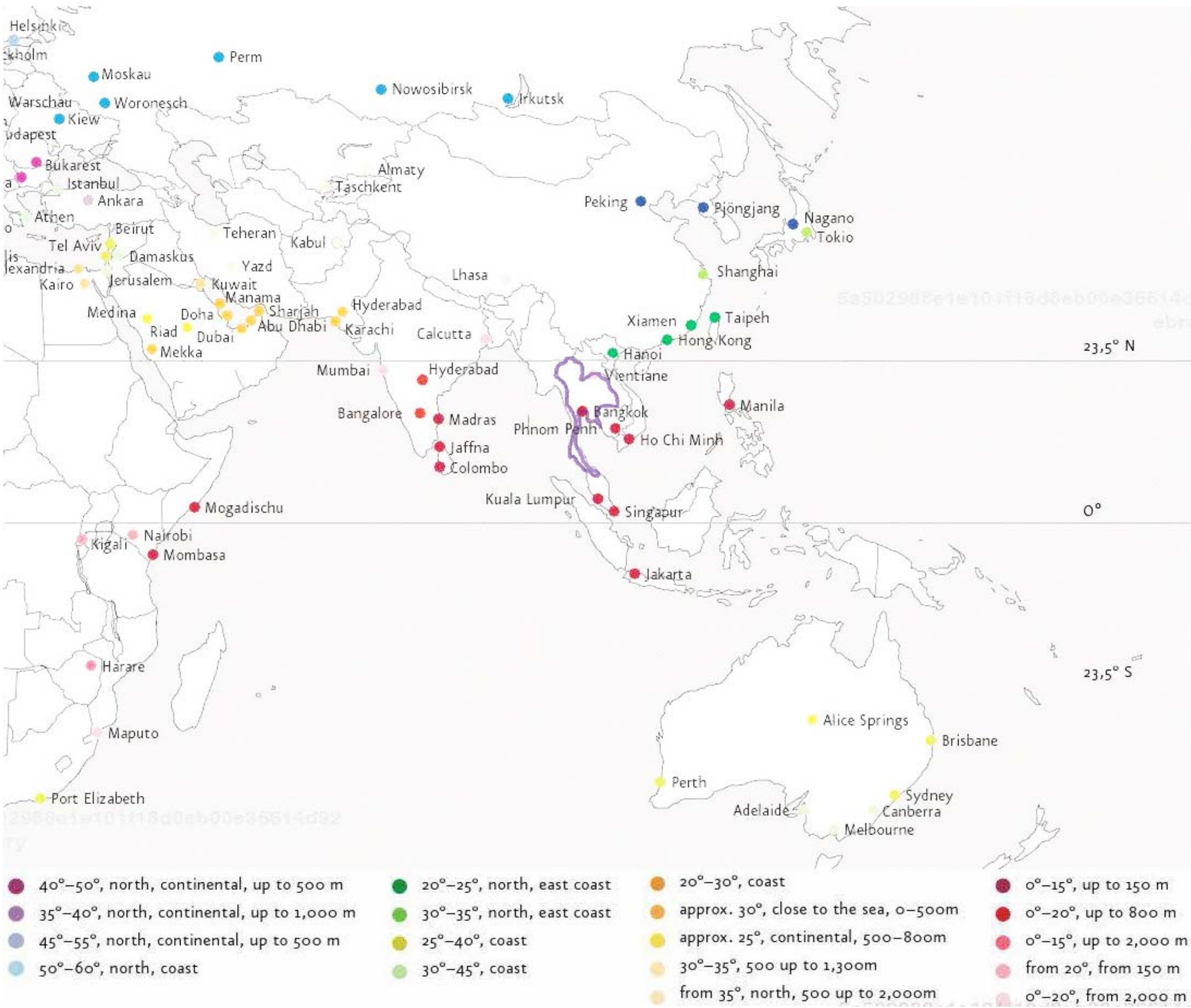


Fig.2. 2 Position of Bangkok, Thailand compare to other cities in different climate zones.

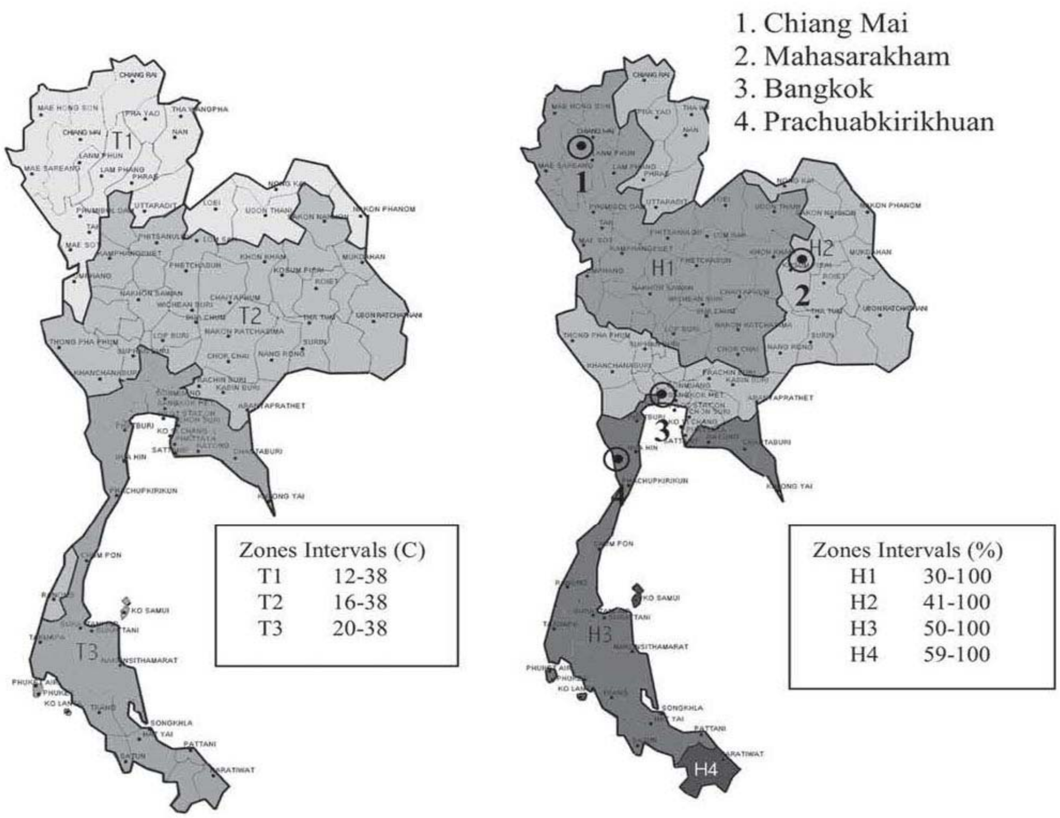
Source: Modified from Hausladen and Liedl (2012)

Warm moist air generally covers the areas in most times of the year. According to records during 1971-2000, the relative humidity is about 64-84% depending on topography. Winter and summer contain lower humidity than rainy season. Clouds are general cover Thailand sky especially in rainy season. Amount of them is normally reduced from November to March due to changes of temperature. Clear sky can be found when the changes are extreme but very rare during rainy season.

Weather in each part of Thailand is different in terms of climate pattern and meteorological conditions. The zones which were categorised by topography consist of Northern, North-eastern, Central, Eastern and Southern Parts, The north contain loads of north to south oriented mountains parallel with main rivers. In the northeast is naturally a large high level plain. The weather of these regions is generally dryer and colder than other parts. The central area is a large low level plain with junctions of rivers form the north oriented from north to south. The weather of this area is generally more humid than the north and northeast. The eastern and southern parts are sea coast area. These areas are dominated by monsoons resulting in more frequently rain in general.

1) Weather data

The focused area for this, Mahasarakham province, is in northeast Thailand. The weather data of the province has been collected roughly because there is no weather station. In order to confirm the data accuracy, the weather data of the area in this study will be compared with weather data from Bangkok and Khonkean, which have been collected by main weather stations. Bangkok is the capital of Thailand located in the central area. The weather station is an agrometeorological station. Since the station was included in the main office of the Thailand Meteorological Department, it is implied to be the most important station of the country. Khonkaen is the province where Khonkaen is one of the major provinces in the northeast. The Khonkaen weather observing station is the nearest weather station to Mahasarakham. Figure.2.3 shows Thailand's weather data zones reported by Yamtraipat et al. (2005) in their study in which Bangkok and Mahasarakham were included. Basically, the relative humidity of Bangkok and Mahasarakham are similar while temperatures in Bangkok are higher.



(a) (b)

Fig.2. 3 Weather data zone of Thailand: (a) temperature and (b) relative humidity with research locations of Yamtraipat et al. (2005).

Source: Yamtraipat et al. (2005)

According to the 30 year (1961-1990) average weather data collected by TMD (TMD, 2012a) shown on Figure.2.4, temperatures in three provinces are generally between 25-35ºC during March to October, which is summer and rainy season. The peaks are generally in April. The areas in the northeast are in Khonkean and Mahasarakam. The maximum temperatures are similar to Bangkok. It is little higher in April and a little lower during winter months. The minimum temperatures are approximately during the summer and rainy season about 5ºC lower than Bangkok in winter. Amounts of rainfall are usually high from May to October. The peak is in September when Bangkok has a substantial higher amount of rainfall than other provinces. Obviously, the amounts of rainfall in rainy season in Bangkok are generally higher than the northeast areas while there are similar from November to April.

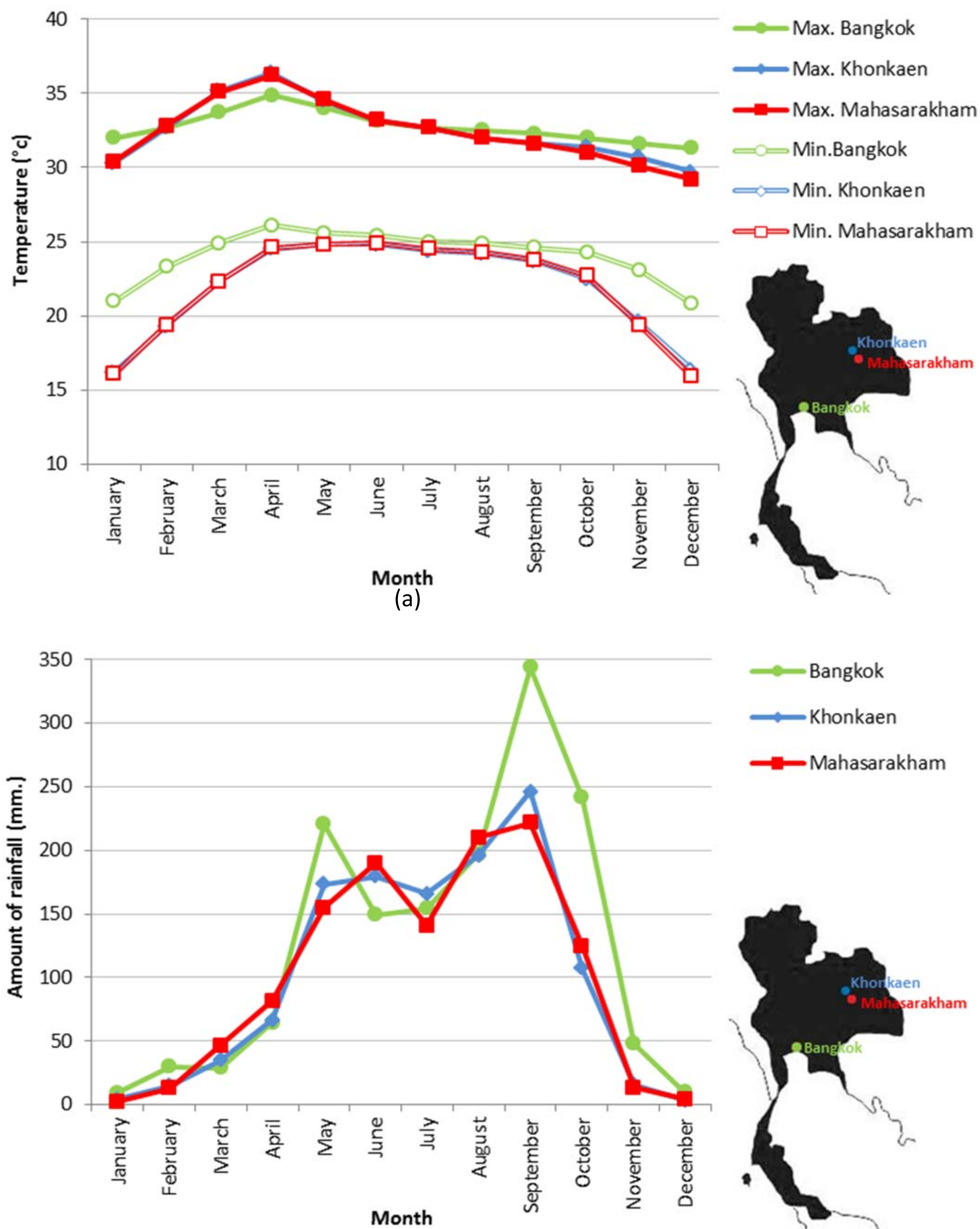
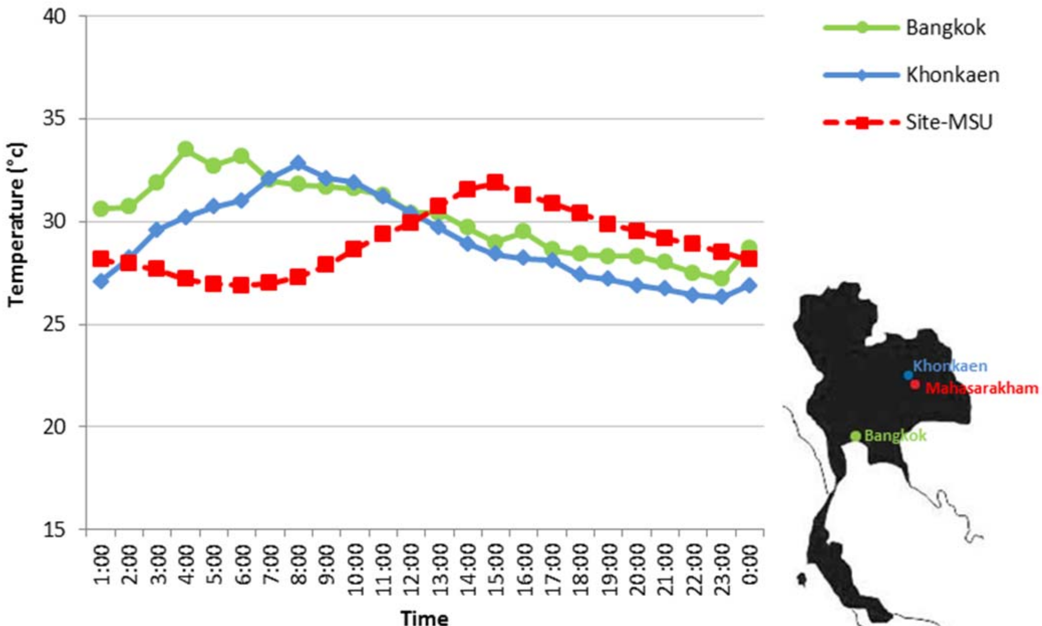
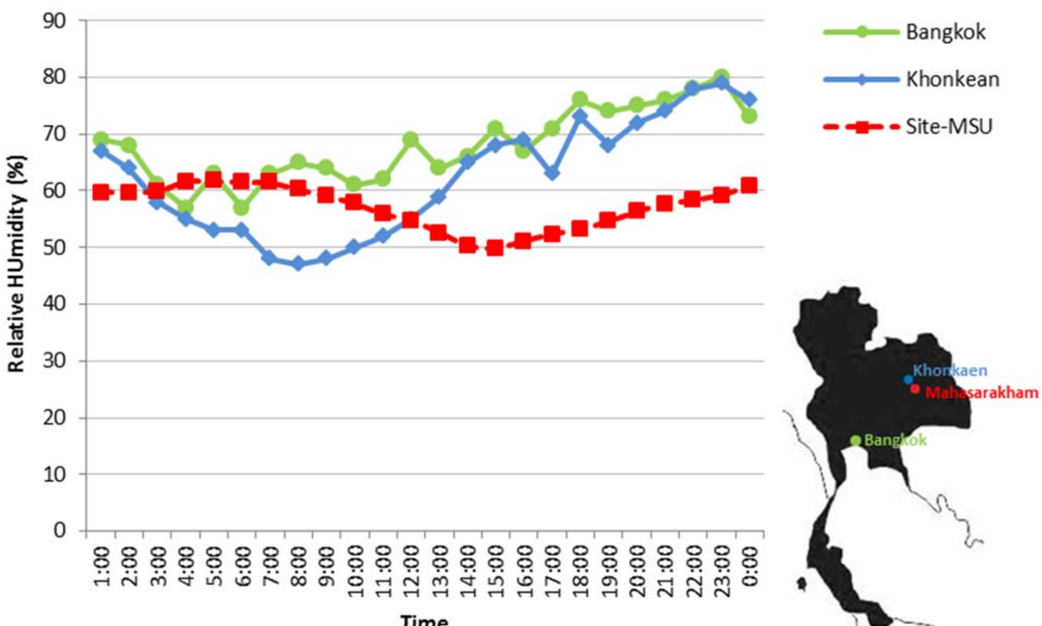


Fig.2. 4 30 year (1961-1990) average weather data for Bangkok, Khonkaen and Mahasarakham: (a) temperature (ºc) and (b) amount of rainfall (mm.).

Source: Using raw data from TMD (2012a)



(a)



(b)

Fig.2. 5 Hourly weather on 19th June 2012 for Bangkok, Khonkaen and case study site, MSU, Mahasarakham: (a) temperature (ºc) and (b) relative humidity (%).

Source: Using Bangkok and Khonkaen data from Thailand Meteorological Department TMD (2012c) and case study site measured by author.

The measured weather data at the case study site may have different patterns compared to data collected from the weather stations, but the differences appear not to be significant (Figure.2.5). During the summer solstice, the temperatures of the area during general working hour are about 27-33ºC while relative humidity values are about 50-60%.

2) Thailand sky conditions

As it was included in tropical climates, Thailand's sky conditions are similar to some areas close to Thailand according to research from Malaysia (Lim et al., 2012) and Indonesia (Rahim et al., 2004). However, there are specific characters which should be focused for a specific area; in this case; it is sky condition, sun geometry and daylight availability of Thailand, and specifically in Mahasarakham.

a. Sky conditions

In general, sky conditions have been classified by the International Illumination Commission (CIE) into three types which are clear sky, intermediate sky and overcast sky, using cloud ratio and the influence of the sun's positions at the observation point as the main criteria (Rahim et al., 2004 and Chaiwiwatworakul, 2011).

Clear sky model represents the sky that is dominated by sunlight and no significant effect from the cloud. Cloudless conditions may theoretically represent this type of sky but the sky which contains less than 30% of cloud can be practically classified into this condition. Luminance distribution can vary dependent on sun geometry. The nearer a patch of sky is to the sun then the brighter it is. The horizontal luminance distribution is brighter compared to the distribution from directly overhead. Therefore, side lighting strategies were suggested for daylighting design for this type of sky. The clear sky condition can be found mostly in some hot climates area and sometimes during summer in colder climates.

The overcast sky is the sky model that the sky is considered full covered by cloud and no effect of sunlight included. Theoretically, its zenith luminance distribution is three time higher than that of the horizon. The overcast sky condition is generally found in temperate climates such as in the UK. Illuminance on the ground of 5000 lux was assumed to be produced by the standard overcast sky for daylighting design purposes (Nicholls, 2002).

The intermediate sky condition has been included representing the illuminance distribution between clear and overcast sky which contain substantial great range of daylight level distribution. In previous research in the tropics such as Rahim et al. (2004) and Chaiwiwatworakul (2011), either cloudy or partly cloudy sky conditions were mentioned as the intermediate type. The conditions were classified using percentage of cloud: more than 70% and between 30-40% respectively.

The sky conditions, especially in tropical zones can vary at the same observation point. From long observation Rahim et al. (2004) confirmed that the intermediate sky is the most frequently sky condition occurring in Indonesia. Chirarattananon et al. (1996) informed that the major sky condition in tropical climates is cloudy sky while Chaiwiwatworakul (2011) stated that partly cloudy skies as the most frequently condition in Bangkok. Chaiwiwatworakul (2011) also claimed that clear and overcast sky conditions can hardly to be found in Thailand. As a long-term study from 1999-2004, the researcher reported that sky was usually clear in December and April.

b. Sun geometry

Sun paths, which generally differ between latitudes, are the key factor in terms of the impact of direct sun. In order to study sun geometry, three astronomical events are assigned to indicate the sun path. These are winter solstice, summer solstice and equinox. Winter solstice is the date that the sun locates at the furthest position from the earth. The shortest day and longest night of the year occur on this date. The day can be different depended on observing location, typically between 20th-23rd December for the northern hemisphere and 20th-23rd June for the south hemisphere. In contrast, summer solstice is the date that contains the longest daytime. It is during 20th-23rd June for the north hemisphere and 20th-23rd December in the south hemisphere. Equinox is the date when the duration of day and night are approximately equal. The event occurs twice a year during the 20th-23rd of March and September. The solstices can indicate the range of sun angles for winter and summer which can be applied the design strategies such as shading design. For temperate zones and higher latitudes, the summer solstice also represents the day that the sun is in the highest position of the sky but sun paths in the tropics are different. In tropical zones, there are some dates between the solstices that the sun locates directly overhead. The date that the sun locates directly overhead was included to this study since the position of the sun not only influences air temperature but also have very high impact on illumination level.

Thailand is in the northern hemisphere between latitudes 5º37’N to 20º27’N. The latitude of Bangkok is about 14ºN and is 16ºN for Mahasarakham. The sun path patterns of the two latitudes are slightly different. The sunpath diagram for 16ºN latitude is shown in Figure.2.6. The winter solstice of Mahasarakham is on 22^{rd} of December with daytime length of about 11 hours. The sun is in the lowest position in the south. The date contains very small altitude of 20º in the southeast and southwest during the edges of working hour: 8AM and 4PM. With the daytime length at about 13 hours, summer solstice is on 22^{nd} of June. The sun influences on the north orientation with the smallest altitude at about 35º in the northeast and northwest. While the date that the sun vertically overhead of Bangkok is on 27^{th} of April and 16^{th} August, it is about 5^{th} of May and 8^{th} August. In Thailand, the hottest date of the year is not on the summer solstice but varies around the end of April, which is average to the first date that the sun is directly overhead. Although it is not an exact date, between 27^{th} April and 5^{th} May can roughly represent the hottest day.

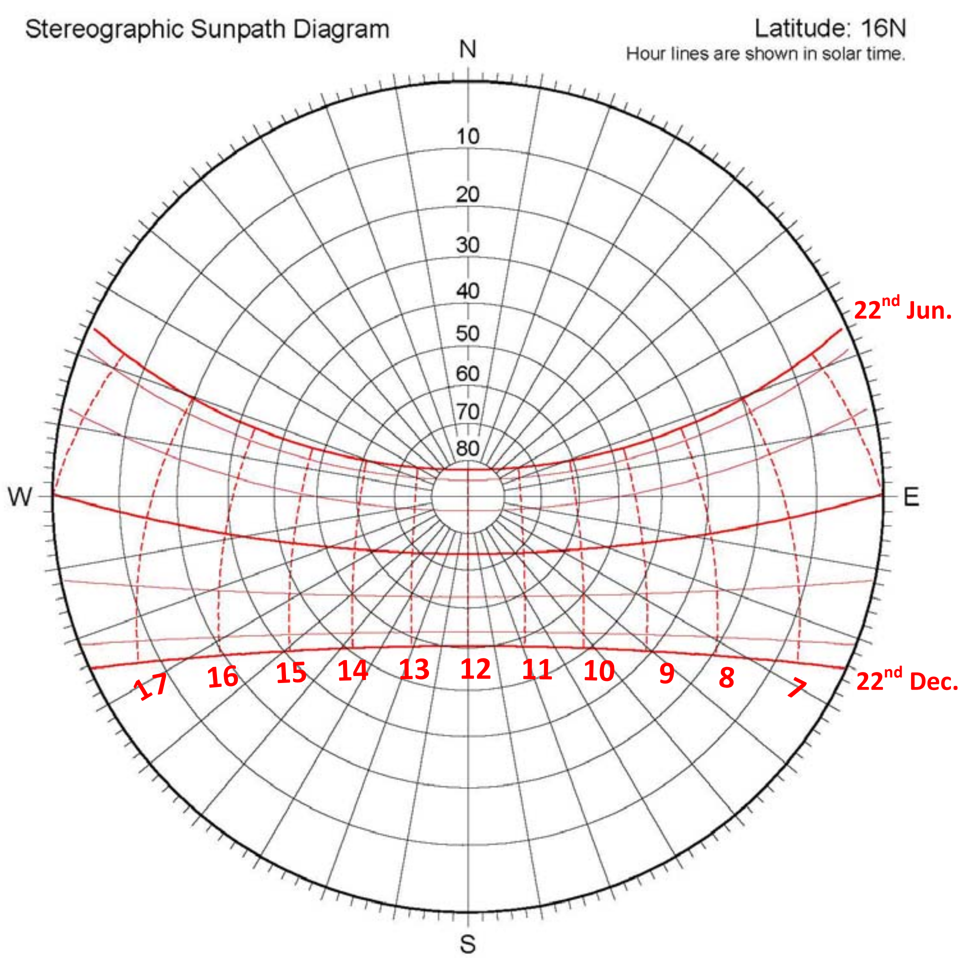


Fig.2. 6 Sunpath diagram for the latitude of 16ºN

Source: Modified from JALOXA (2014)

Consequently, for daylighting studies of the area the significant dates which should be considered are summer and winter solstices. For the thermal aspect, the date that the sun is directly overhead should be applied instead of the summer solstice.

c. Daylight availability

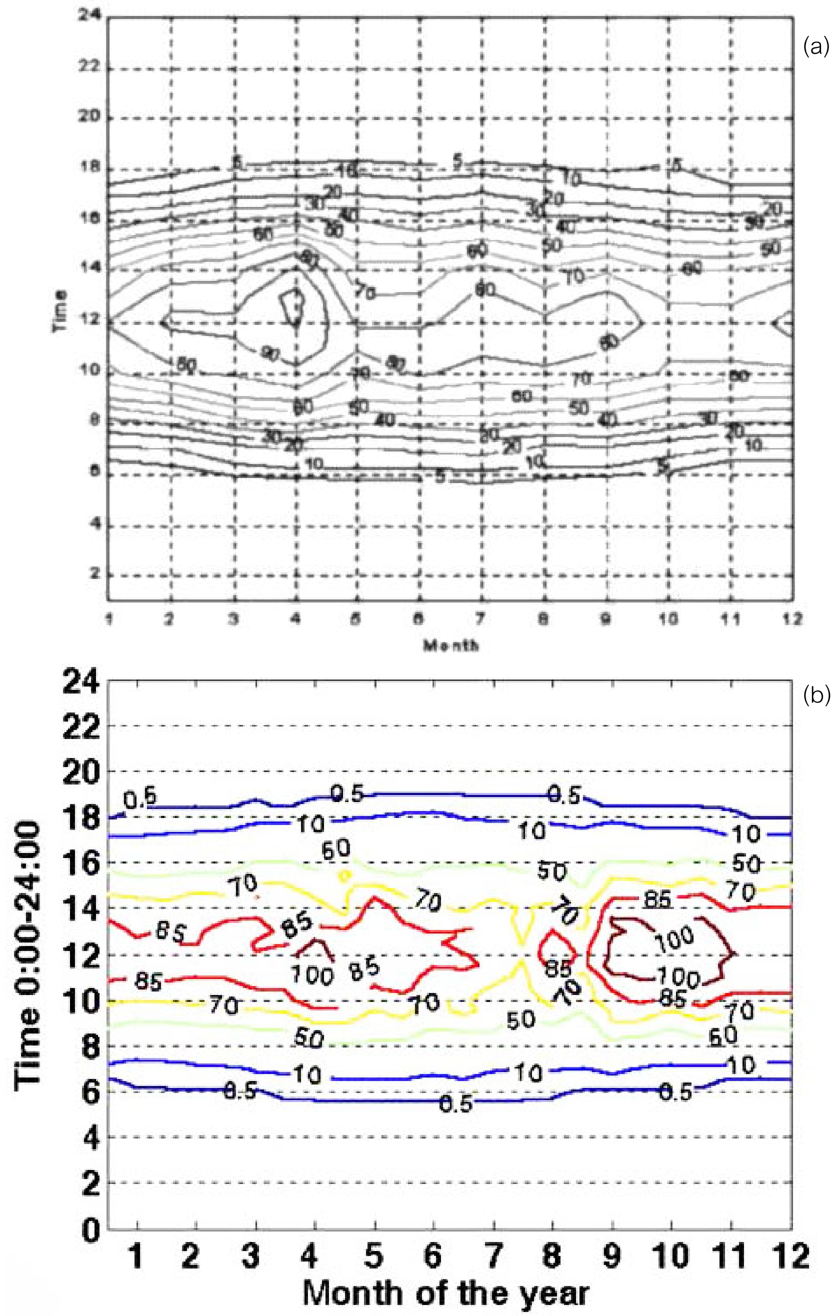


Fig.2. 7 Global horizontal illuminance (klux) in Thailand: (a) at AIT weather station Bangkok and (b) in Mahasarakham.

Source: (a) Chirarattananon et al. (2002) and (b) Pattanasethanon et al. (2007)

The availability of natural light in tropical climates for daylighting is obviously overwhelming. However, Edmonds and Greenup (2002) pointed out that internal illuminance of buildings in tropical climates is rather much lower than that in temperate climates. There is relatively little literature regarding daylighting availability for the tropical skies. Investigating an office building in Malaysia, Lim et al. (2012) confirmed the availability of tropical daylight. Daylight availability in Bangkok has been investigated by Chirarattananon et al. (1996), Chirarattananon et al. (2002) and Chaiwiwatworakul (2011). Chirarattananon et al. (1996) illustrated the high efficiency of daylight in Bangkok by reporting diffuse horizontal illuminance values of more than 10,000 lux being exceeded 93% of the time. Chirarattananon et al. (2002) stated that the average value of global illuminance is approximately 105,000 lux throughout the year for all window directions, which confirms the very high potential of natural light for daylighting. Mean hourly data of global illuminance and irradiance obtained from the AIT meteorological station in Bangkok during 1999-2004, Chaiwiwatworakul (2011) showed that the values were high throughout the year. There is little difference between June and December, even though there should be some difference.

As the only research in the area, Pattanasethanon et al. (2007) demonstrated that Mahasarakham illuminance levels are generally much higher than Bangkok because the sky contains lower amounts of cloud. The comparison is shown in Figure 2.7. The results therefore can confirm the availability of daylight for building daylighting in the case study site.

2.3 Thermal aspect of façade design

The facade is the main medium of the building that is involved with not only visual but also thermal aspects. For daylighting design in the tropics, the use of natural light should be optimised for the most illumination level while controlling heat and glare. Apart from daylighting itself, thermal comfort strategies are also required to be considered. This section will review theories of human thermal comfort strategies in tropical climates.

1) Human comfort

Human thermal comfort is that condition when people are satisfied with their thermal environment. Thermal comfort is recognised as one of the most important determinants for environmental design. Factors, standards and assessment of thermal comfort are the key knowledge required in order to understand and achieve a satisfactory thermal environment.

a. Factors of thermal comfort

Influential factors of thermal comfort can be divided into two categories: personal and environmental factors. Personal factors depend on the occupants individually. It consists of metabolic rate and clothing level which relates to occupants' bodies and activities. There are four environmental factors; dry bulb air temperature, mean radiant temperature, air velocity and relative humidity.

Human metabolism is the system by which bodies transform the chemical energy of food and drink into heat energy by undertaking metabolic activities. *Metabolic rate (met)* expresses the level of the transformation per unit area of body surface. Met rate varies in different types and duration of activities. Casual activities such as sitting results in a lower met rate (~1 met) than activities involving movement like walking or running (~2 or 3 met). Apart from activities, eating habits and body shape are additional influential factors for human metabolism.

Clothing level (clo) in this context means the thermal insulation value of the layer of clothing. The proportion of the body that is clothed is also required to be considered. Due to the fact that clothing is the main medium between people skin and surroundings, it influences the thermal balance of the human body, reducing heat loss, for example. However, trousers and long sleeved shirts made of insulated materials, such as wool, can produce too warm discomfort.

In terms of temperature (ºC), there are ambient air temperature, operative temperature and mean radiance temperature that relate to human comfort. *Air temperature* or dry-bulb temperature (DBT) can be commonly measured by a dry-bulb thermometer as it stands for average temperature of the air surrounding occupants excluding influence of radiation and moisture in the air. The temperature can indicate the amount of heat without moisture and is important for building design in curtain climates. *Mean radiant temperature (MRT)* is the temperature that can indicate exchange of radiant heat energy between surfaces of two adjacent objects: in this case; human body and surroundings which can be objects of the air. The temperature level depends on differences between the human body and surroundings surface temperatures and their abilities to absorb and emit heat. As it is associated with thermal balance of the human body MRT is more important than air temperature for indicating thermal comfort, particularly in hot climates due to the fact that more solar radiation influence inside buildings and people wear lighter clothing which allows more radiant heat transfer. Although MRT relates only to the human body, thermal comfort in buildings relies on both surface and air temperature. Concept of *operative temperature* is combination of the former temperature metrics. It is also known as equivalent temperature or effective temperature. The temperature describes not only heat transferring by radiation but also convection, which is directly related to air temperature and velocity. Operative temperature can be roughly approximated to air temperature in low thermal mass buildings.

For human comfort, *air velocity* or air speed is the average speed of air movement that the human body exposed to. Too much air velocity can increase skin heat loss and cause discomfort especially for cold climates. More clothing level is required for this condition. However, it can help improve conditions of high relative humidity when people are sweating and reduce discomfort in hot and humid conditions.

Relative humidity (RH) is a humidity metric that indicate the percentage of amount of water vapour in the air and amount of saturated water vapour that the air could hold. When it is considered in a thermal comfort context, excessive high humidity can normally obstruct sweating. Sweating is a cooling strategy of the human body whereby the human skin attempts to reduce its temperature by evaporating when it is overload. When the effectiveness of sweating is reduced, discomfort generally occurs.

b. Comfort assessment

Many methods have been used to assess human comfort. These are generally complicated combinations of the comfort factors together. In this study, two methods which have been frequently mentioned in previous studies will be compared. There are thermal indexes: TSENs and DISC and assessment methods such as PMV, CSV and two-node models; and a new method called adaptive thermal comfort.

TSENS index is the model used to predict the vote of thermal sensation. Predicted Mean Vote is the main method applied for this index. *Predicted Mean Vote (PMV)* is the thermal assessment method which applied empirical studies by surveying how people feel in a given thermal environment with heat balance equation of human skin temperature. *Predicted Percentage of Dissatisfied (PPD)* is another method which was developed from PMV based on very precisely controlled conditions. Disregarding human thermal adaptation, PMV and PPD models assume that all occupants are in the same condition where a room temperature is not influenced by changes of weather. With this concept, due to only one temperature set, occupants never have to adapt to other thermal conditions. At least 80% of participants' votes is required for indicating their thermal comfort. The method is one of the main models that thermal standards such as ASHRAE Standard 55-2010 applied to examine occupants' satisfaction for thermal conditions inside buildings. Thermal comfort for these methods can be presented using devices such as temperature-relative humidity chart or psychometric chart.

The methods were developed by 'Fanger' (Fanger, 1970) focusing on participants' vote of their thermal sensation in a given condition using seven thermal sensation scales: -3=cold; -2=cool; -1=slightly cool; 0=neutral; +1=slightly warm; +2=warm and +3=hot. However, there are other similar scales such as 'ASHRAE' and 'Rohles and Nevins' that using scales from one to seven or containing ten scales from -4 to +5 respectively. Bedford, in another scale format, used seven scales of much too warm=1, too warm=2, comfortable warm=3, comfortable=4, comfortable cool=5, too cool=6 and much too cool=7. They were categorised into *Thermal Sensation Vote (TSV).* Thermal sensation votes mainly result in how people feel in their thermal sensation, whether cold or hot and how they rate what extent of that feeling. Kim et al. (2013) reported that PMV is inadequate to indicate human thermal comfort sensation. Basically, predicted thermal sensation is a useful method that can be applied to determine people's satisfaction. Fanger, therefore, suggested the range of comfort between -1(slightly cool) and 1(slightly warm) for the Fanger PMV model and further developed the model into PPD to simplify indications using percentage of dissatisfied instead. According to Markus and Morris (1980), the PMV scales range of -1 to 1 is lower than 30% of PDD. *DISC index* rather predicts the scale of thermal discomfort vote using *Comfort Sensation Vote (CSV)* as the method to indicate whether occupant feel comfortable in each condition. The levels of intolerable, very uncomfortable, uncomfortable, slightly uncomfortable and comfortable were assigned for the index. Some of CSV models such as have similar scale as PMV. Gagge's DISC, for example, applied seven scales of coldness levels as negative values, neutral as zero and warmness levels as positive values.

The *adaptive comfort model* is different to all the models mentioned above. It uses the concept that the room's thermal environment is influenced by outdoor climate and that people can adapt their circumstances to achieve comfort in different temperatures. Occupant surveys are the main method of this model. Depending as it does on occupants' behavioural, physiological and psychological characters, the model appears complicated and subjective. The significant factors which can make the PMV impracticable for naturally ventilated buildings are the influence of thermal expectations, perception or familiarity of previous thermal sensation and reaction to control thermal environment of occupants on their satisfaction votes. The model indicates that in natural ventilation environments occupants can accept and prefer a wider range of temperatures than enclosed spaces with air conditioning system where outdoor weather has no significant impact on occupants' thermal preference. On the other hand, applying air conditioning system is recommended to be avoided in this method. ASHRAE 55 standard has also applied the adaptive comfort model as an alternative, with recommendation of 80-90% satisfaction. Other standards, such as European EN 15251 and ISO 7730, also applied in the model with different details.

In general, all of the methods can be categorised into two main alternatives for application purpose. While the TSENs and DISC methods such as modified PMV model are appropriate for thermally controlled conditions, adaptive comfort model should be selected for natural ventilation environments.

c. Comfort zone

Comfort conditions have been suggested by many standards with various methods. The methods basically used the comfort factors to be parameters (Visitsak, 2007). When previous research specific to school design for thermal comfort (e.g. Wong and Khoo, 2003 and CHPS, 2006) was considered, ASHRAE Standard 55 was frequently referred to. The standard applies a psychometric chart to demonstrate comfort zones and design strategies. The chart illustrates relationship between temperature and humidity containing multiple axis indicating values of operative temperature; wet bulb temperature; humidity ratio and relative humidity (see Figure 2.8).

ASHRAE (2010) recommended operative temperatures of 21-26ºC and 24-28ºC with various RH values to represent comfort zones for high and low clothing levels respectively. High RH can be included in the comfort zone when it does not exceed 80% and the temperature is low. Figure 2.8 shows that the comfort zone can be moved to a higher range of temperatures when wearing light clothes. According to Visitsak (2007), the shift of comfort zone is also for summer. The two zones overlap mostly at temperature of about 25ºC, which can be assumed as a mean value. However, there are other standard used for thermal comfort. For example, a CIBSE benchmark of 18-5ºC was applied to analyse thermal comfort by Le Hong and Rodriques (2013).

Tab.2. 8 Ranges of Tropical Summer Index for various thermal sensations

Thermal sensation	Range (ºC)	Optimum value (ºC)
Cold	< 23.8	-
Comfortably cool	23.8-26.8	25.5
Neither cool nor warm	26.8-29.5	28.0
Comfortably warm	29.5-32.0	30.8
Hot	> 32.0	-

Source: Sharma and Ali (1978)

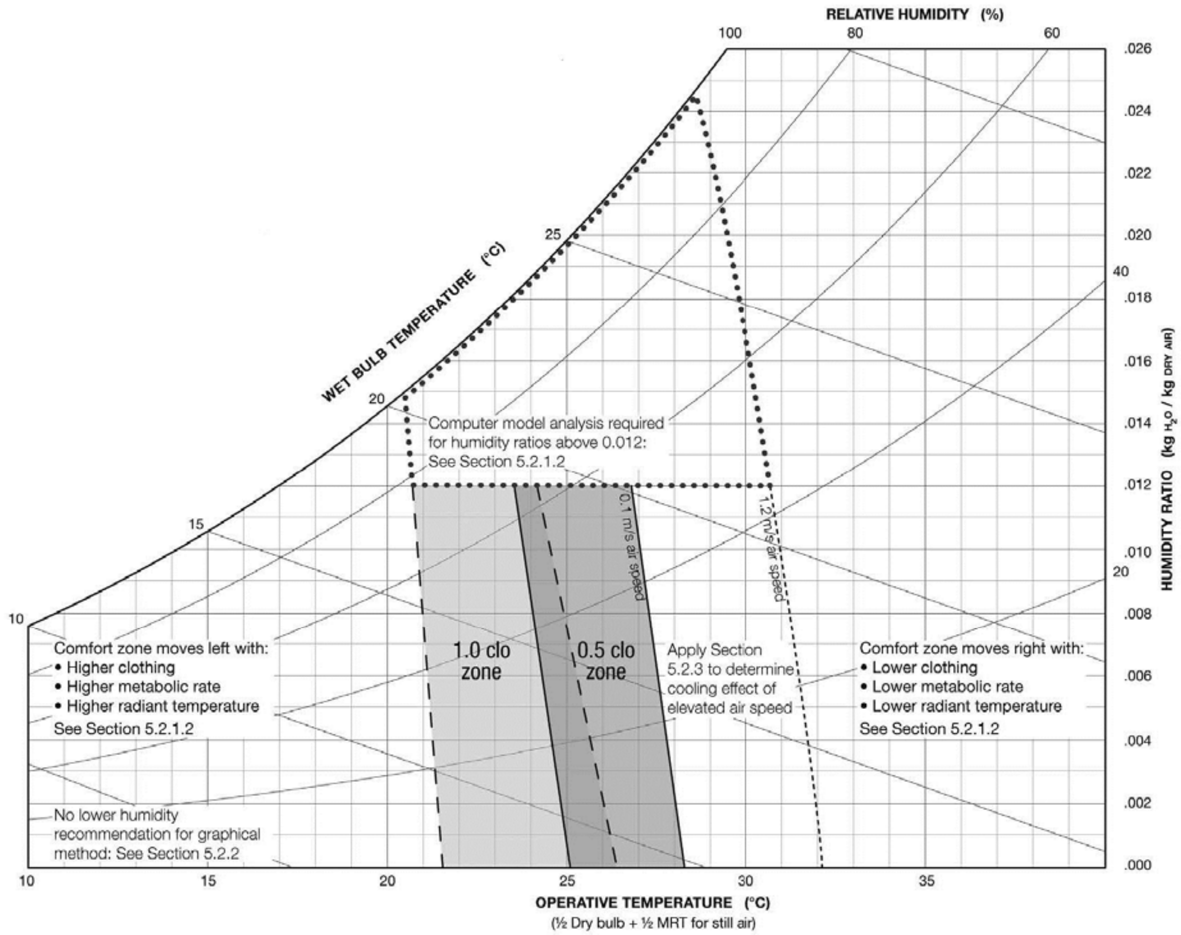


Fig.2. 8 Comfort zone of ASHRAE Standard 55-2010 (Copyright © 2010 by ASHRAE)

Source: ASHRAE (2010)

For a tropical climate, Sharma and Ali (1978) presented the temperature range of thermal sensation at 23.8-32ºC and optimum values of 25.5-30.8ºC representing comfort conditions (Table2.8). Mishra and Ramgopal (2013) concluded from previous comfort studies in hot humid climates that the comfort zone in buildings with air conditioning system is in range of 22-28ºC. While the neutral temperature is about 24-27ºC, users' preference is generally colder than neutral. Similarly, in a classroom study, Wong and Khoo (2003) found that the occupants accept cool more than warm conditions. Comfort temperatures of air conditioning rooms were confirmed by Mishra and Ramgopal (2013) to be lower than passive areas. For RH, Yamtraipat et al. (2005) found that high RH never affected occupants' comfort unless room temperature was high at about 26-27ºC. According to their surveys, 50-60% of RH was recommended.

2) Design strategies for tropical climates

The tropical zone contains different ranges of climates from dry to wet and from hotter to warmer. For hot humid climates like Thailand the weather may vary due to time and season changes but it generally contains high temperatures and high humidity levels. Many previous researches, such as Khedari et al. (2000), reported empirical weather data collection at the focusing site and found that majority of weather data were not in comfort conditions. As shown in Figure 2.9, the Bangkok climate is generally hotter and more humid than comfort of ASHRAE 55. The data indicate that building occupants are generally facing excessive warm discomfort condition in general. Thermal comfort strategies can be concluded in psychometric chart such as shown in Figure 2.10. The comfort zone can be extended using strategies such as heating, cooling, evaporating, humidify and dehumidify; or combinations of them depending on weather conditions. Natural ventilation, surface cooling system and night ventilation may be considered for hot humid climates but the strategies offer very limited cooling possibilities (Hausladen and Liedl, 2012). Therefore, cooling and dehumidify are obviously the key solutions for improving building environments to be comfort.

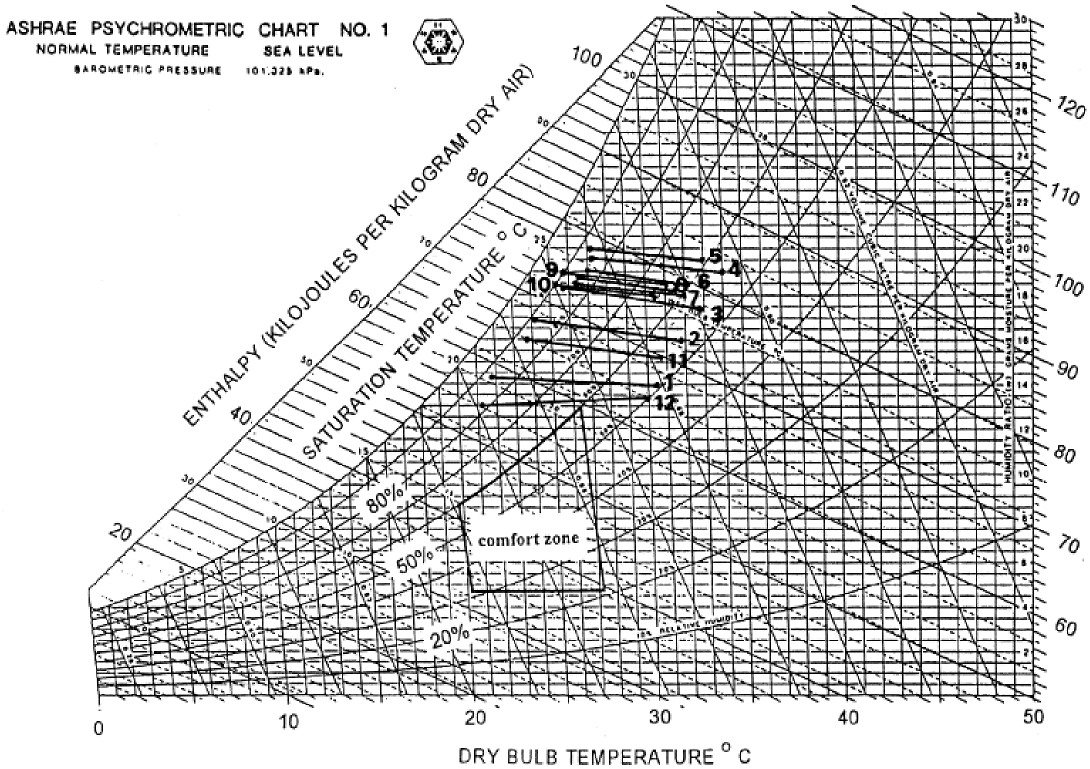


Fig.2. 9 Plots of monthly daily mean of Bangkok climatic conditions at two times of the day in Psychometric chart with ASHRAE recommended comfort zone.

Source: Khedari et al. (2000)

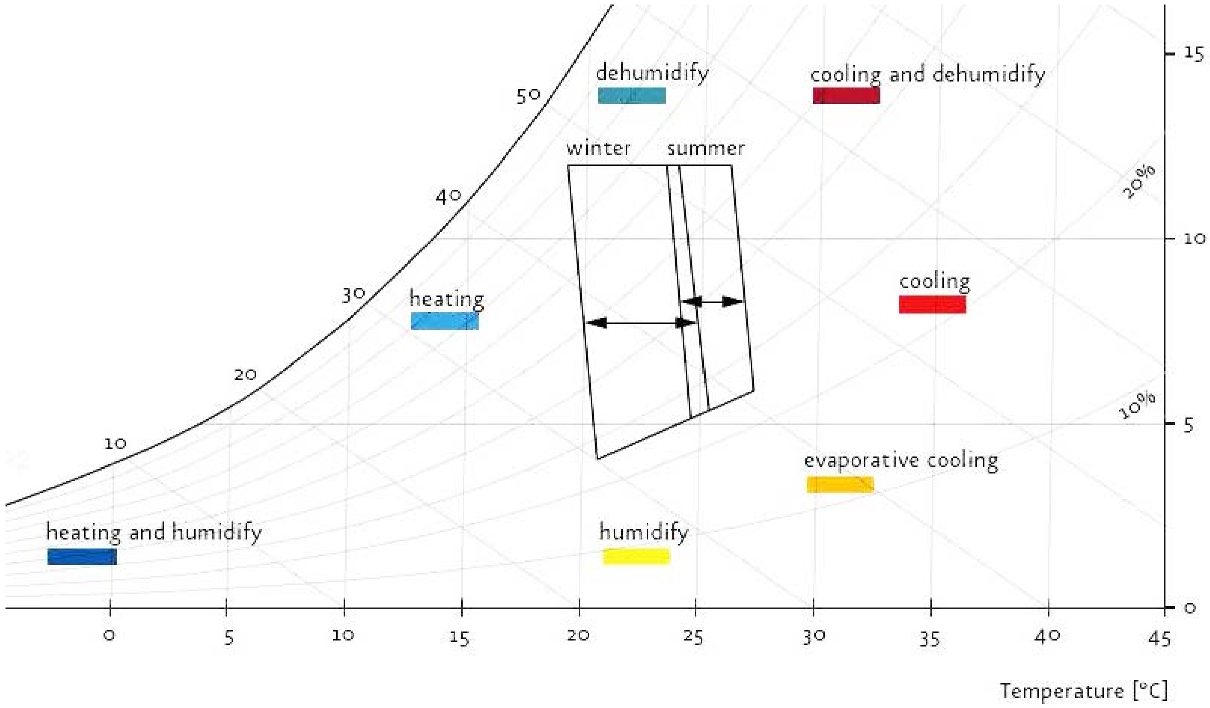


Fig.2. 10 Comfort improving strategic Psychometric chart.

Source: Hausladen and Liedl (2012)

For spaces that require environment control an air conditioning system is more necessary. In an environmental rating of classroom (CHPS, 2006), designs of building envelope and mechanical system were suggested to control the thermal comfort factors in order to provide thermally comfortable environments.

When energy conservation was concerned, CHPS (2006) suggested that the energy performance of new construction school designs "must be at least 10% less than a standard design". Yamtraipat et al. (2005) stated that the recommended indoor setpoint of air conditioning system for Thailand is 26ºC which was accepted by most occupants of all climatic zones. Thirakomen (2001) suggested that humidity control had been ignored when applying air conditioning systems in tropical climates; a RH of not more than 50% of RH was recommended as the controlling threshold.

For the building envelope, balancing the area of opaque and translucent materials with the choice of their properties is the main design consideration. In Thailand, the Energy Conservation Promotion (ECP) Act requires $\leq$50 W/m^2 of Overall Thermal Transfer Value (OTTV) for educational buildings. The application of OTTV stands for average amount of heat transferring into a chosen building through its envelope. The method was valued by Chirarattananon et al. (1996) and is similar to ASHRAE and Singapore standards. The equation of OTTV is:

$$OTTV = (U_w)(TD_{eq})(I - WWR) + (U_f)(DT)(WWR) + (SF)(SC)(WWR) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

where U_w = heat transfer coefficient of opaque wall

U_f = heat transfer coefficient of fenestration

WWR = window-to-wall ratio

TD_{eq} = the equivalent temperature difference across the wall

DT = temperature difference across the glazing

SF = solar factor

SC = shading coefficient of fenestration

The equation contains heat transfer by conduction in the first two parts for the opaque envelope and glazing respectively. Excluding material properties, the proportions of wall and window area is the main variable. For the last part, factors of radiated heat transfer also contain window area. This reveals the significance of window size in heat transfer. However, other factors - solar factor and shading coefficient - also imply that proper orientation and more shading can lessen the problem.

"For a typical building in Bangkok, the wall comprises plastered brick (of 80 mm. width and with the overall thermal transfer coefficient or *U*-value of 3.0 $Wm^{-2}K^{-1}$) and the window comprises single glazing (of 6 mm. thickness and with a *U*-value of 5.9 $Wm^{-2}K^{-1}$) with reflective-grey coating (rendering a shading coefficient of 0.6)." (Chirarattananon et al., 2000: p.331). The typical use of building materials in Thailand has been accepted as necessary not only due to availability of the materials but also resulting from the skills and familiarity of workmen. Therefore, the proportion of opaque and translucent materials becomes the major factor for façade design. It can be explained by Eq. 2.5 that for thermal control, the window area should be minimized while consideration of window orientation and shading strategies are needed for avoiding solar radiation.

2.4 Reviews of façade design for daylighting

Focusing on façade design for daylighting, researchers reported many discrepancies. Because their studies are very site specific and contained various factors such as building type, season and climates, they may not be directly comparable and difficult to justify whether they are practical for the current study. Currently, there is a lack of research relating to façade design for daylighting in tropical classrooms. However, some studies were found in related areas. Daylighting in offices in the tropics, for example, applied similar brightness requirements, although space activities and occupants' behavior are different. Because daylighting design has been intensively studied for a long time in western countries, especially in Europe and

North America, architects in warmer areas have generally applied western guideline directly without any concern over different climates. However, it is possible that not all of those recommendations are practical. As a result, this review will discuss previous research in daylighting related topics in order to justify proper façade design solutions for daylighting in tropical classrooms.

1) influential façade design parameters

Investigating façade design for daylighting, Gagnel and Andersen (2010) considered the window-to-wall ratio WWR, window position, glazing transmissivity, type and the size of shading devices. Apart from adding the reflectance of room and window, Torres and Sakamoto (2007) selected the same parameters. They emphasized the impact of reflection strategies by including a lightshelf as one of focused parameters. Saridar (2004) highlighted the impact of room features by considering the influence building shape, window feature (consisted of orientation, size, shape and ratio to wall), relationship of window to room dimension and shading devices. Perez and Capeluto (2009) studied the influence of parameters for energy conservation in hot-humid school buildings suggested that the influential parameters consisted of insulations and thermal mass, building envelope colour, ventilation and infiltration, building shade, window features and lighting control system. For daylighting there were only shading devices, window features and lighting systems involved. Surprisingly, these daylighting parameters were found to be either *very significant* or *significant* for reducing energy consumption compared to the other parameters. A school windows guideline suggested by the University of Minnesota (2011) recommends window design strategies of window orientation, daylight control system, window area (WWR), shading device and glazing type. The strategies were suggested to be ranked by order of importance. Although having similar parameters, Perez and Capeluto (2009) pointed out that the impact priority probably is lighting control systems, glazing type, window size, window orientation and window shading respectively. While the other parameters were rated as *very high impact*, the shading device was found just to have *high impact.* The research findings imply complicated relationships between parameters. Therefore, a priority of parameter impacts cannot be decided easily.

According to a review of shading impacts, shading devices appear to have a lower impact than other parameters. Perez and Capeluto (2009)'s conclusion on shading importance was that the use of a device can considerably increase the influence of glazing type, which actually has a higher impact. In terms of cooling load reductions window shading was also found have less impact in school buildings in Oman compared to other thermal parameters and glazing type respectively (Zurigat et al., 2003). However, while no significant impact was found for insulation strategies and glazing types in summer, the impact of shading devices was experienced all year round.

Montazami et al. (2015) comfirmed the neccesity of optimising internal environment factors. For environmental design in UK schools it was stated that it will not be successful unless architects take all impact parameters in to holistic considerations. For instance, not only the optimum area of windows but also the combination of compatible shading sizes can really advantage daylighting and heat and glare control. Another important example would be the relationship between glazing type and shading device, which was already been mentioned. As reported by Perez and Capeluto (2009), optimised shading devices including proper control can dramatically reduce the impact of glazing type. In terms of materials, glazing type has been greatly developed so that some with high technological adaptations can solve most daylighting difficulties (Steemers, 1994 and Leroux and Gosselin, 2012) but the implementation of them is being questioned regarding whether they are practical in the tropics (Edmonds and Greenup, 2002). Moreover, the more to high technology is less it practical in school buildings. The design of educational buildings, especially in developing countries, requires passive systems which do not need much cost and effort to construct, operate and maintain due to a lack of support funds and available experts. For those reasons, the impact of glazing type becomes limited.

In agreement with the previous studies mentioned, excluding glazing type, the main façade parameters considered in this study consisted of **window orientation**, window features and **shading devices**. For specifying window features parameters such as size, shape and position were considered but in the contexts of shape and function of spaces. For classrooms, window features are normally specific in each study. Above the working plane it is the height that windows have been placed in general classrooms while along seating areas it is the window width that is important. Studies of window dimensions can be varied by height, width and position. However, it has been frequently scoped by applying the ratio or percentage of **window area** instead.

2) Other obligatory parameters

As a highly influential parameter, daylighting control systems consisting of shading operations and lighting controls may not actually represent façade design, but it was raised for daylighting design by many pieces of research e.g. Leung and Fung (2005), Winterbottom and Wilkins (2009), Van Den Wymelenberg (2012), Samani and Samani (2012) and Alrubaih et al. (2013). A reduction of artificial lighting load has generally been used for assessing how daylighting strategies can benefit energy conservstion. According to that previous research, not lighting alone but combining lighting and shading controls can improve both energy savings and visual confort.

Additionally, orientation and behavioural pattern of users (why and how they adjust window blind for instance), were strongly suggested to be considered for daylighting strategies in classrooms (Theodorson, 2009; Alrubaih et al., 2013 and Montazami et al., 2015). Occupants' preference and behaviour probably lead to differences uses of lighting; specific patterns of lighting controls can result in an improved lighting environment. Montazami et al. (2015) comfirmed these findings by sayling that a lack of understanding of occupants' response is one of the main reasons that causes most of the UK school designs to not achieve their environmental goal although they can succeed in their building design.

Since a proper balance of window shade and lighting was believed essential and high impact of occupants' behaviour was found to be significantly correlated with the strategy, daylighting control strategies and occupants' responses became compulsory and have been included as influential façade parameter.

3) Window area

Apart from daylighting, window size was assumed to be involved with visual, acoustic and thermal comfort conditions and students' learning performance. The University of Minnesota (2011) stated that without daylighting control more window area simply led to more energy consumption. Less window area can solve difficulties of heat and glare control. Catalina and Iordache (2012) argued that large window area can benefit IEQ and energy conservation significantly whereas it had no major impact on operative temperature. Similarly, Le Hong and Rodriques (2013) affirmed that glazing area influences daylighting and lighting energy use much more than thermal aspects. In terms of total energy conservation, window area decisions require to know to what extent that daylighting can save lighting energy while cooling or heating load increase because of heat loss or gain from large windows. A large window area is well known to generally increase cooling load while reducing lighting load in hot climates. In a tropical climate, Chungloo et al.(2001a) invertigated a office building in Thailand and found that although daylighting can lesson lighting use substantially, total electricity still increased when larger window areas were applied. The findings reveal that cooling energy load was a higher impact than lighting load. Chirarattananon et al. (1996) also reported that increasing window area can actually reduce lighting energy although it has negative effect in terms of heat gain.

When recommendations for window area were reviewed, many discrepancies were found in previous researches (summary shown in Table 2.9). For tropical climates, great ranges of glazing area between 10-81% of the façade area were recommended for buildings in Brazil. The percentages quoted are numerous - smaller area for wide rooms while larger areas for narrow rooms (Ghisi and Tinker, 2005). In a study in Gaza (Muhaisen and Dabboor, 2015), 10% of wall area was suggested to be the optimum window area for thermal aspects (heating and cooling energy conservation). The researchers further affirmed that this was the proper window size also for the visual aspect. Binarti (2009) suggested a combination of clerestory and eye level windows for classroom in Indonesia. Recommended window area was a WWR of 20% and WFR of 11%. In a hot humid climate in India, Maitreya (1979) suggested at least 13% and 20% of classroom floor area for unexposed and exposed fenestration area respectively. Considering electric energy saving in an office building in Thailand, Buriprasert (2000) recommended a WWR of 0.4-0.5 to be optimum for clear glazing, while Chungloo et al. (2001b) suggested a WWR of 0.3-0.4 for high visible transmittance and solar cooling load glazing with shading device and Less than 0.5 WWR for clear glazing window. In the same city, Chirarattananon et al. (1996) suggested a more strict WWR between 0.05-0.25 for optimum energy consumption. These recommendations are totally different and have too many specific conditions to generalise or indicate general trends for applying to design.

For subtropical regions, Rupp and Ghisi (2012) recommended a great range of window areas between10-100% of the façade area for commercial buildings depending on room shape and window orientation. However, many pieces of research rather suggested to limited window area. For residental building, 10% of total wall area was recommended by Muhaisen and Dabboor (2015) whereas Inanici and Demirbilek (2000) suggested 25% of façade area. As required illuminance is higher, larger areas of window were suggested for classrooms. Contrastingly, not more than 15% of room floor area was suggested by Boneh (1982). For glare in office spaces, 40-55% of a wall being glazed causes e glare when occupants sit facing the window (Boubekri and Boyer, 1992). Zannin et al. (2008) supported the view that a WWR of 0.40 was probably too large, resulting in glare and significant thermal effects.

Even in warmer climates the suggested window areas vary from 30 to 100% of the façade area (Inanici and Demirbilek, 2000; The University of Minnesota, 2011 and Leroux and Gosselin, 2012). While the University of Minnesota (2011) recommended 30% of façade area to minimiseg energy use, espacially from cooling load, and suggested larger areas for north and south facing façades, Leroux and Gosselin (2012) suggested 30% for north orientation and claimed thate heating energy can be most saved. However, approximately 20% of glazing to floor areas was recommended for north orientations to provide good daylight for UK classrooms (Robson, 1874). For south facing, 70% of façade area and 100% of WWR was suggested by Inanici and Demirbilek (2000) and Leroux and Gosselin (2012) respectively. In addition, Le Hong and Rodriques (2013) suggested 35% of WWR for north orientation, 45% and 70% for west and south orientation repectively for UK office spaces. For lighting and thermal aspects, there were ranges of 30-70% of external facade was recommended for various orientations of seven metres depth classrooms in a secondary school in Jersey, Channel Islands (Steemers, 1994). When comparing to other climates, glazing area recommendations in cold climates appear to be similar in each orientation, with 30-35% WWR for the minimun on north and 70-100% WWR for the maximun on south façade.

Tab.2. 9 Suggestions for window area from previous research.

No.	Window area	Specification(s)	Indicator(s)	Location/ climate	Reference
1.1	WWR 0.3-0.4	High T_{vis} and SC glazing with shading device	- DF(overcast sky)- Electric lighting energy saving	Bangkok, Thailand 13.76°N, 100.5°E Tropical (hot humid)	Chungloo et al. (2001b)
1.2	WWR < 0.5	Clear glazing window			
2	WWR 40%-50%	For office building	- Illuminance - Energy saving	Bangkok, Thailand 13.76°N, 100.5°E Tropical (hot humid)	Buriprasert (2000)
3	0.05 < WWR < 0.25	With shading device	- Illuminance - Electric lighting and cooling load	Bangkok, Thailand 13.76°N, 100.5°E Tropical (hot humid)	Chirarattananon et al. (1996)
4	window area: WWR 20% and WFR 11% Clerestory height: 0.4 of room width and ≤11% of room height	- For high reflectance classrooms (glazing size should be higher if the room reflectance is low) - Combination of eye level window and clerestory	- DF(overcast sky) - Cooling load reduction	Yogyakarta, Indonesia 7.80°S, 110.36°E Tropical	Binarti (2009)
5.1	10-33% of the façade area	For wide rooms	- DF(overcast sky) - Energy saving	Florianópolis, Brazil 27.6°S, 48.55°W Tropical (warm humid)	Ghisi and Tinker (2005)
5.2	20-81% of the façade area	For narrow rooms			
5.3	largest area	- For large rooms and narrow rooms - Window orientation: south*			
5.4	smallest area	Window orientation: north* and west			
6.1	13% of floor area	For unexposed fenestration area	- Illuminance - Temperature - Ventilation	India 21°N, 78°E Tropical (hot humid)	Maitreya (1979)
6.2	20% of floor area	For exposed fenestration area			
7.1	10-100% of façade area	- For commercial buildings** - In cooling condition	integration of daylighting and artificial light	Florianópolis, Brazil 27.6°S, 48.55°W Tropical (warm humid)	Rupp and Ghisi (2012)
7.2	largest area	- For narrow room - Window orientation: south*			
8	WWR <40	- For classrooms - Clear and overcast sky	- Glare - Thermal discomfort	Curitiba, Brazil 25.42°S, 49.25°W Subtropical (warm humid)	Zannin et al. (2008)

No.	Window area	Specification(s)	Indicator(s)	Location/ climate	Reference
9	10% of total wall area	Residential building**	- DF(overcast sky) - Heating and cooling energy saving	Gaza Strip 31.42°N, 34.33°E Subtropical (hot humid)	Muhaisen and Dabboor (2015)
10	≤10-15% of room floor area	- For classrooms - More than one side for good ventilation	- Daylighting - Thermal aspect	Israel 31°N, 35°E Subtropical (warm humid)	Boneh (1982)
11	25% of the façade area	- For Residential building** - Window orientation: south	Thermal performance	Izmir, Turkey(warmest city) 38.42°N, 27.13°E Subtropical (Hot dry)	Inanici and Demirbilek (2000)
12	Large windows on two sides	For classrooms	Students' learning performance	USA: California 37°N,120°W Subtropical Washington 47.5°N,120.5°W Subtropical (warm humid) Colorado 39°N,105.5°W Temperate	Heschong et al. (2002)
13	< 40-55% of wall area	- For office (frontal position) - Partly cloudy sky	intolerance glare	USA: Texas 31°N,100°W Subtropical	Boubekri and Boyer (1992)
14	70% of the façade area	- For Residential building** - Window orientation: south	Thermal performance	Erzurum, Turkey(coldest city) 39.91°N, 41.28°E Temperate (continental)	Inanici and Demirbilek (2000)
15.1	WWR 70%	- For office spaces - Window orientation: south	- Daylighting - Thermal aspect - Energy saving	UK: 51.5°N, 0.12°W Temperate	Le Hong and Rodriques (2013)
15.2	WWR 45%	- For office spaces - Window orientation: west			
15.3	WWR 35%	- For office spaces - Window orientation: north			
16	20% WFR (1/5)	- For classrooms - Window orientation: north	- Daylighting - Heat and glare control	UK: 51.5°N, 0.12°W Temperate	Robson (1874)
17	30-70% of external facade	- For 7 metre depth classrooms - Window orientation: various	- Daylighting - Thermal aspect	Channel Islands, UK 49.42°N, 2.33°W Temperate	Steemers (1994)
18.1	≤ 35% of the gross exterior wall	- For classrooms - Window orientation: west and east (larger for south and north)	N/A	Minnesota, USA 46°N, 94°W Temperate (continental)	The University of Minnesota (2011)
18.2	0.3<WWR< 0.45		Minimum annual energy use		
18.3	WWR ~0.3		Lowest peak cooling		
19.1	WWR 30%	- For office building - Window orientation: north	Heating energy saving	Quebec City, Canada 46.82°N, 71.22°W Temperate (continental)	Leroux and Gosselin (2012)
19.2	WWR 100%	- For office building - Window orientation: south			

*reverse sun geometry for north and south window orientation in the southern hemisphere

** require lower illumination level than educational buildings

Variations in window area recommendations are obviously due to climates zones and research locations. More percentage window area appears appropriate to colder climates, especially when focusing on thermal performance. In a hot climate, Thai's Rating of Energy and Environmental Sustainability also generally suggests to avoid using large window area because of thermal aspect (TGBI, 2013). However, not only do the recommended ranges appear too large to apply for design but suggestions for the same climatic conditions also contain significantly different values. The difficulties probably result from the different requirements of building types. Different lighting levels and occupant behaviour can cause a variation of environmental assessment. Moreover, another difficulty is the variety of window area metrics that have been applied. *Window to wall ratio (WWR)* appears to be most preferred as it was applied in many studies, such as Zannin et al. (2008), Binarti (2009) and The University of Minnesota (2011). *Percentage to total wall area* (Muhaisen and Dabboor, 2015) and *Percentage to the facade area* (Ghisi and Tinker, 2005 and Rupp and Ghisi, 2012) generally represent a proportion of window area to internal wall. These ratios obviously can be directly compared. However, other metrics have been utilised. *Percentage of the gross exterior wall* appeared in The University of Minnesota (2011). At the same number of percentage, window area in *percentage of the gross exterior wall* is slightly smaller than that of WWR. Larger area of gross exterior wall is due to the addition of room floor structures, which are not shown inside the room. However, the fact that these proportions are based on the same idea and have little difference allows a rough comparison with minor errors. As an indicative alternative, *window to floor area ratio (WFR)* was generally applied (Catalina and Iordache, 2012 and Binarti, 2009 for instance). While WWR associated with width and height of rooms, WFR rather indicate importance of room size which is one of influential daylighting parameters. Some of previous research such as Binarti (2009) suggested two of them for referring both approaches but most studies selected one. For studying their relationship, simple calculation was obtained for various room dimensions: 3-12 metre width and depth and 2.5 to 4 metre height. The results show that WFR of 15% which was selected to be base case is equal to numbers of WWR from to 11.25-72%. Obviously, the calculation can confirm incommensurable of the ratios. Variation of WWR also implies that each room dimension can cause different to the ratios. Therefore, not only conflicts among suggested metrics but all recommendations also appear too specific in exact room proportions leading to limited to apply for other room sizes.

Apart from general eye level windows, some types of additional window were recommended. Top windows have been proved to improve illumination level. Binarti (2009) suggested a combination of eye level window and clerestory for classrooms in Indonesia. A clerestory height at 0.4 of room width and not more than 11% of room height was recommended can optimise daylight factor and reduce cooling load (Binarti, 2009). More than one side windows also advantage visual comfort (Tanner, 2000), improving students' learning performance (Heschong et al., 2002) and ventilation (Boneh, 1982). However, the proper window area for this solution remains a question. While large two side windows was confirmed can improve highest students' learning performance, smallest windows area was recommended to optimise daylighting with thermal performance.

Glazing area can vary in different contexts. Factors that influence window size include window orientation, room size, room reflectance and building materials. Window orientation was widespread indication while other factors were normally fixed in each study. Lack of knowledge of them was found.

The effect of window orientation on window area is normally caused by the influence of sun geometry. For north facing; either large or small window was recommended. While west and east window was suggested to be avoided or minimised, larger window area was generally suggested greatly for south orientation (The University of Minnesota, 2011). From tropical to temperate climates, the largest window area was generally recommended for the south orientation (e.g. Ghisi and Tinker, 2005; Rupp and Ghisi, 2012 and Leroux and Gosselin, 2012). Discrepancies in recommendations can arise possibly because almost all of previous research results were obtained under overcast sky conditiosn which have little impact from direct sun. When considering sky conditions, the overcast sky has been accepted for temperate climates in general but not for the tropics (Chirarattananon et al., 1996). Even in temperate aresa where the sky is generally overcasts, significant impact from low angle sun from the south occurs. As a result, the application of overcast sky to tropical research probably results in errors of daylighting prediction.

Ghisi and Tinker (2005) reported optimal window size for daylighting and energy conservation that depended on not only climate or window orientation but also the proportions of rooms. Ghisi and Tinker (2005) and Rupp and Ghisi (2012) agreed that large rooms and narrow rooms required large windows in order to improve daylighting and conserve energy. However, the results of daylighting and energy conservation might not always agree. The researchers suggested that wide rooms may have higher potential for daylighting than deep rooms but for energy consumption a narrow room was better due to less heat loss and gain. For reflectance of the room, high reflectance probably brings best results for reflected strategies. Binarti (2009) suggested that less room reflectance larger window areas are required whether at eye level windows or clerestory windows. Supansomboon (2001) argued that room reflectance has less impact on window area but it does influence top windows significantly. When consider Binarti (2009)'s suggestion, it is possible that when windows were enlarged for benefitting rooms with lower reflectance, top windows were included. However, reflectance of room interiors should not be less than 50% (Supansomboon, 2001). In terms of buildng materials, Leroux and Gosselin (2012)'s research reveals that combination of opaque and glazing materials has great impact on thermal aspect. In other words, optimised window area also depended on material selection. However, clear glass may not have high performance but Chungloo et al. (2001b) reported that only less than 0.5 WWR of clear glazing window can save 30-50% of lighting electricity.

4) Shading devices

Shading devices was generally recommended for controlling solar heat gain and glare while some types, such as a light shelf, can increase illumination levels. A significant impact of shading device on thermal comfort and energy conservation was emphasized for many climates, particularly in cold climates (Palmero-Marrero and Oliveira, 2010). Shading devices also benefits uniformity of daylight distribution and glare decrease (Wong et al., 2004). Apart from those purposes, shading devices was required can be operated to darken classrooms in some circumstance (CSBR, 2011). Significantly, shading device was rated more important than WWR for lighting energy saving because more depth of shading device was required when window was larger and it considerably reduced room illuminance. However, increase of WWR can reduce influence of shading device (Chungloo et al., 2001b).

Many pieces of research according to Denan (2004)'s review agreed the necessity of shading devices in the tropics. External shading devices were affirmed to be practical solutions for improving daylighting in a tropical office building in terms of quantity and quality (Lim et al., 2012). In tropical climates window design aims to allow daylight while avoiding heat transfer and glare. Large shading devices are essential in order to protect direct. Light constructions with wide awnings and verandas are types of shading devices that use to applied to traditional buildings (Edmonds and Greenup, 2002). However, shading device are claimed to reduce excessive high illuminance but fail to improve lighting quality (Denan, 2004).

Shading design depends on orientation, season, sky conditions and sun altitude. The University of Minnesota (2011) suggested that the device is most appropriately applied to south facing windows. The guidance did not mention about north façades, while Rea (1984) and InnovativeDesign (2004) suggested no shading device for north orientations because the direct sun has little effect in very northern area like Canada and the USA. Differently, David et al. (2011) found that shading device were still essential for north orientations in the tropics. However, although more shading depth was required in winter Kim and Kim (2010) found no significant difference between projecting depths for visual performance.

Many types of shading device have been investigated for different purposes. Only daylighting or sunlight protection was considered in this review. Evaluating shading performance for daylighting, Dubois

(2003) compared the performance of different types of shading device. White screens, blue awning and tilted venetian blind provided acceptable illuminance, uniformity and luminance ratio for both VDT screen and paper tasks. The white screen provided highest illumination level and most preferable luminance ratio while the best case for uniform illuminance was venetian blind. Overhang, horizontal venetian blind and white awning appeared to provide highest illuminance which was acceptable for seeing paper task but too high for the use of computer screen. Overhang was rated the poorest device in terms of uniformity ratio (Dubois, 2003). Coloured screen such as grey screen may bring about unacceptable daylight environment, but it was the best device in terms of occupants' preference.

Studying shading devices of north and west office facades in a tropical climate, David et al. (2011) ranked the overhang as the best solar protection for north orientation. It also provides more external view for occupants. However, it was found to hardly reduce heat gain from solar irradiation compared to other shading types. Moreover, a simple type of overhang appeared to have limited efficiency in terms of providing visual comfort. For west facing windows tilted louvers were recommended. Side fins provide better lighting quality by significantly reducing room luminance. Varendorff and Garcia Hansen (2012) stated that two-dimensional shading may generally provide more protection capacity than top horizontal shading but it cannot be guaranteed that the better shading ability will provide more visual comfort. It is because visual comfort metrics such as DGP does not depend on effect of direct sun alone

There are some related literatures obtained in other climate zones. In a study in Korea, Kim and Kim (2010) suggested shading devices such as tilted slats, overhang and horizontal venetian blind can respectively enhance daylight for south orientation facades. Examining five façade retrofit alternatives for an office building in a mild climate, Martinez et al. (2012) suggested a combination of overhangs and fins as the most effective sunshade that can save 12.8% of total energy. According to Perez et al. (2012)'s research in Spain, south facing rooms with a reflective fragmented light shelf can significantly reduce solar radiation while illuminance dropped as much as 100 lux compared to a no shading room. Blinds appeared more effective as illuminance was approximate to the room without shade whereas solar radiation can be greatly reduced. In a hot climate, the study of Freewan (2014) revealed that the devices which provided more contact to outside also bring about more daylight quantity. On the other hand, more covered devices, such as a diagonal fin, may not be proper for outside interaction but it can satisfy users and benefit human comfort.

As studies mentioned above, the shading type that provided high performance for daylighting and sun protection appeared to be horizontal devices such as the overhang and venetian blind, whether containing horizontal or tilted slats. Vertical fins were assessed that can protect from an oblique, low angle sun and reduce room luminance but they never achieved good daylighting unless a horizontal device was integrated. Screens and awning were hardly raised for thermal aspect although some conditions of them appear to have high daylighting performance. Consequently, horizontal devices will be focused on for this study.

In terms of sizing, many metrics was used for indicating shading sizes in general. Wong et al. (2004) suggested external shading devices with a shading coefficient of at least 0.55 can provide an illuminance standard of 300 lux in an office in Singapore. In Korea a projecting depth for south orientation devices of 0.8 metres was suggested as the most appropriate for daylighting and sun shading (Kim and Kim, 2010). Apart from shading coefficient and shading depth, there is a shading proportion such as overhang depth to window height ratios as a shading size indicator. Variations of indicators are one of the difficulties. Furthermore, most previous research suggested either too general or too specific solutions without condition details such as shading type. These findings may not be able to implement. However, there are two shading types that were frequently focused specific in classrooms. These are overhangs and venetian blinds.

Overhang and other diffusion devices can improve illumination distribution for sidelighting in school classroom but also increase the heat load of the room (Higuchi et al., 2009). Concordantly, Varendorff and Garcia Hansen (2012) reveal that adding more depth of shading appeared not to be a proper solution in terms of not only seeing outside view but also visual comfort. Saihong and Srisutapan (2007) found that there is no significant difference between straight and curve shape of devices. For overhangs alone, there are two suggestions for tropical climates. With an infinite width, the depth of overhang was recommended to be equal to the height of the windows (David et al., 2011). .According to a study of an office building in Thailand, an overhang depth to window height ratios (D/H) at 0.4-1.0 can reduce about 10-18% of cooling load (Chungloo et al., 2001a) and 2-25% of lighting load (Chungloo et al., 2001b) various by WWR and glazing materials.

Due to the fact that the application of overhangs generally brings about inadequate daylight level, additional functions such as light shelf were introduced. Investigating combinations of overhang and a light shelf in a southeast facing classroom in Thailand, Saihong and Srisutapan (2007) recommended a 1.2 metre depth light shelf and a 0.6 metre depth overhang as sufficient size for sun protection, excluding r winter. In winter, a venetian blind was suggested. Chou et al. (2004) indicated that a combination of overhang, top window, light shelf and artificial light (shown in Figure 2.11) can improve the uniformity ratio and minimum illuminance. This is probably because the overhang under top window also represented light shelf. For the eight metre depth of southeast facing classrooms in Taiwan, minimum illuminance was found to meet the standard of 500 lux. Additionally, lighting energy consumption can be reduced by about 34.6%. Studies by Chou et al. (2004) and Ho et al. (2008) reported that illumination levels were commonly sufficient but lacked uniformity because of the considerably higher illuminance at the area in front of the window. The device was modified by adding an internal light shelf, external lower layer light shelf and vertical panel in various sizes and positions. In terms of position, lower light shelfs can increase illuminance but increasing rates occurred near windows where illuminance already was high. The addition of an internal light shelf, the lower layer of light shelf and combination of vertical panel and double layer light shelf, respectively, may reduce illuminance but the illuminance still met the standard. It also resulted in more uniformity. The researchers suggested that the reflection from additional devices may be able to improve illumination level and uniformity ratio. However, all of them can improve neither lighting quantity at the furthest area from the window nor uniformity ratio to meet the suggestion of 0.5. Therefore, integration of artificial light at the furthest row from the window was recommended.

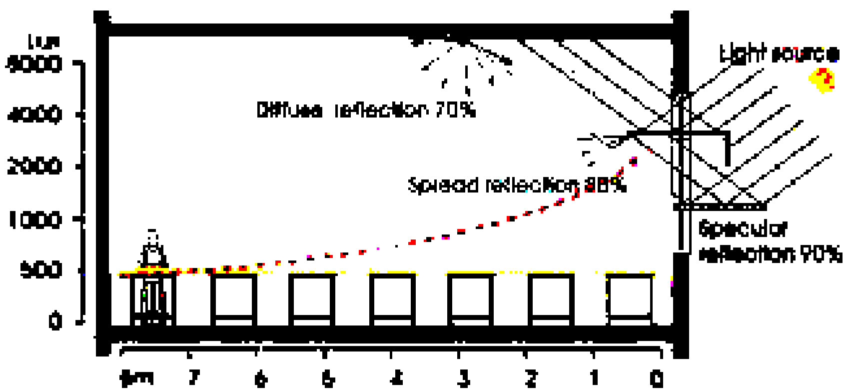


Fig.2. 11 Facade solution for a subtropical classroom which sufficient illuminance and appropriated uniformity was affirmed.

Source: modified from Chou et al. (2004)

Although a suggested size of overhang is unclear, previous research findings reveal combinations of light shelves that can improve lighting quantity. Instead of fully shading, partly protection of the device was recommended. Edmonds and Greenup (2002) also felt that direct sunlight can be an important advantage for tropical climates when thermal and visual control was integrated. Consequently, small-depth separated device is possibly proper solutions that are the same concept of louvre and venetian blind.

For louvers (David et al., 2011), the size of the device depended on the number of blades. Smaller number of blades was recommended for better daylight level and visual comfort. On the other hand, smaller louvers which contain more than five blades resulted in worse visual results with on additional solar protection benefit. In this study, 45° tilted louvers were suggested for west facing.

For venetian blinds, horizontal and sloped slat was recommended in different conditions. Horizontal venetian blinds were confirmed can reduce considerable amount of incident daylight and simultaneously diffuse the daylight into the building (Alrubaih et al., 2013). In a southwest orientation classroom in Thailand, Saihong and Srisutapan (2007) suggested a 0° slat angle of venetian blinds for best daylighting in summer. For winter, the angle 60° was recommended to control glare. A research aiming to save energy for an office space in Korea (Yun et al., 2014) reported different results. The angle of venetian blind slats for a south facing window was recommended as 0° for winter and 30° for summer. The 30° slat was affirmed able to deal with glare whereas the 0° slat allowed occurrence of glare. While Dubois (2003) suggested 45°, a sloped degree of 20° slat was suggested by Kim and Kim (2010) in order to maximise illumination and good view. It is sensible that horizontal slats were applied for high sun altitude conditions whereas slats were tilted for low angle sun positions. However, as closed or more angled slats cannot sufficiently facilitate daylighting to achieve visual comfort (Chaiwiwatworakul et al., 2009), other types of shading device were recommended to combine with venetian blinds.

Shading strategies were examined that can significantly reduce illumination level, therefore, a combination of reflecting strategies have been introduced to be daylighting techniques. Reflecting devices such as light shelf, louvers, prismatic glass and venetian blinds have been widely applied for decades (Steemers, 1994) due to the fact that it can protect from direct sun, increase illuminance and control glare. When comparing to clear window, window luminance can be increased by up to 50% using white venetian blind whereas outdoor view can be decreased by up to 66% (Dubois, 2003). For more efficiency, high reflectance slate was recommended: Kim and Kim (2010) suggested 70% reflectance for example. However, reflective device also can cause glare from reflecting light or reflected surface, especially in winter when the sun altitude is usually low (Alrubaih et al., 2013). As newer strategies, light guiding shade (LGS), laser cut panel (LCP) and light pipe can practically improve illuminance to achieve satisfactory levels in offices in sub-tropical and tropical climates. Angle selective glazing with LCP can facilitate both natural ventilation and daylighting. Its adjustable louvers can suit differences of season, totally close in winter to avoid ventilation and reflect the light to room ceiling for instance. However, due to higher costs and complicated technology, these techniques are probably impractical for applying in educational buildings in developing countries. Steemers (1994) argued that although the cost was very expensive these devices can reduce not only total energy consumption but also glazing area (which is one of the main building costs). Effectiveness of high technology adjustable shading like electrochromic glazing has been proved for more than two decades but Edmonds and Greenup (2002) claimed that it was impractical in the tropics. The same as double skin that may be practical for some cold climates but Martinez et al. (2012) affirmed that it have no significant impact on energy conservation in this case.

5) Window orientation

Window orientation appears to have a very high impact on energy consumption and visual comfort in all circumstance. According to Maitreya (1979), different window orientations provided temperature differences about 1ºC in classroom in a hot humid climate. It is mainly because influenced by sun geometry on building façade, particularly when direct sun beam shines on the façade. In addition, it is the only façade parameter that has to be considered in early stages of architectural design (The University of Minnesota, 2011). According to studies regarding façade design in various aspects, one façade orientation generally focuses on one piece of research. Very rarely are they focused in the different visual and thermal performance in each orientation whether cardinal or not i.e. north, south, east and west or ordinal: northeast, northwest, southeast and southwest.

Studying daylighting performance of a classroom in Brazil, Zannin et al. (2008) focused on all orientations in both cardinal and ordinal directions. They affirmed that window orientations in north to south axis had better daylight distribution than other axes. Due to an effect of small sun altitude, orientation in ordinal directions allows more exposure to daylight. Especially for the northwest to southeast axis, it is either excessive or sufficient daylight level in general, therefore, control is required. A study in an ordinal orientation educational building in Thailand illustrated that classrooms facing southeast have the most visual problems (Saihong and Srisutapan, 2007). A study of classroom daylighting in Concepcion, Chile (Piderit and Bodar, 2012) concluded that the lighting environment of west and east orientated classrooms never archived visual comfort criteria even when top lighting strategies were included. Without sufficient evidence that all orientations were simultaneously investigated, many pieces of research and daylighting guidelines such as Boneh, 1982; Ghisi and Tinker, 2005; The University of Minnesota, 2011; Rupp and Ghisi, 2012 and Leroux and Gosselin, 2012; suggested avoiding west and east window facing and, instead recommended north and south orientations. While The University of Minnesota (2011) strongly suggested south orientation that is the best solution, it was ranked as the worst condition in Muhaisen and Dabboor (2015)'s study. Daylighting in north orientation classrooms was found steadiest and less hot (Wu and Ng, 2003) containing a fair quality of illuminance and uniformity. South facing classrooms appeared to have better visual performance than north orientations, particularly when top lighting was combined (Piderit and Bodar, 2012). Differently, Boneh (1982) suggested the north orientation to be the best solution while south orientations can be treated with shading devices. Most environmental research in Thailand appears to agree with Boneh (1982), Buriprasert (2000) for example, recommended north window orientation to optimize the daylighting strategy because less solar factor and large angle of the sun affect windows in a few mouths of the year. Large window area with less shading device which can enhance most natural light was allowed.

It is sensible for avoiding west and east orientation because small angle sun which mainly affect on these directions resulting in difficulty to control heat and glare. Interestingly, the effect occurs only for half day and it will be less impact if working hour of focused space is limited before and after sun is in low altitudes. Orientation in ordinal directions still questions whether it has the most opportunity for daylighting or worst case in terms of heat and glare control. In the north hemisphere, south orientation also contains low angle sun especially in winter solstice in most area. It may be difficult to protect direct sun but optimum sun patch can advantage thermal performance by passive solar heating particularly in warm or cold climate countries (Wu and Ng, 2003). For hot climates, direct sun is generally avoided because of overwhelming heat transfer. A North orientation has less effect by the sun but is limited in the amount of daylight distribution in the room. Integration of electric light was frequently suggested as compulsory for daylighting in north orientations in tropical climates (Buriprasert, 2000). For the southern hemisphere, the suggestions of west and east orientations were reasonably similar while recommendation of south and north orientations which supposed to be inverted from the north hemisphere recommended approach. All in all, there are some conflicts and questions for selecting proper shading device. Despite the same climate, influences of sun geometry and window size generally cause difficulty to specify optimal size of shading devices.

6) Daylighting control

Apart from benefiting learning performance (Tanner, 2000), daylighting control has been known as one of the most influential daylighting parameters that can bring successful results to environmental design. Compatible system of shading device and lighting operation was confirmed to benefit energy conservation in general. In a tropical climate, Chaiwiwatworakul et al. (2009) examined automated blinds with the use of dimmable lighting and found they could save up to 80% of lighting energy in a building in Bangkok. Furthermore, visual purpose appeared to have more impact especially for classrooms. While an automatic system was found convenient and efficient, manual control was found necessary for environmental aspect of classrooms (Straka and Aleksic, 2009). Daylighting control systems have been investigated for a long time in specific topics such as façade or lighting automatic operation systems, occupants' behaviour in daylighting control and environmental achievement of integration technologies. Research in automatic systems is generally specific in office spaces while for classrooms and other non-commercial buildings users' response research is much less. Containing types of operation and building function, the literature can be divided in to façade operation and lighting system.

Façade operation was rated to be a significant factor of daylighting and energy conservation. Van Den Wymelenberg (2012) affirmed that a study of daylighting will be in great error if patterns of window blind use are not included. As the researcher's review, apart from physical needs such as to improve brightness condition, needs of blind operation depends on other three factors which are individual sensitivity, psychological aspect and social factors. When all factors were considered, daylighting and visual contact to outside obviously were found the main reason for having window and opening blind. On the other hand, privacy was claimed to be the major reason for blind occlusion while brightness reduction appeared not much significant. Minority of blind occlusion was found because of direct sun. Thermal comfort was ranked to be the least important factor. Differently, Theodorson (2009) pointed out that the main reason of blind occlusion generally was to darken the room for multi-media presentation. Direct sunlight and glare control were also significant, especially for south orientation. Respectively, to limit view, heat control and privacy are minor reasons. For classroom, neither occurrence of glare nor disturbance of sun beam but blind occlusion mainly depends on learning activities. For instance, presentation media which needs a dim environment was confirmed to be one of the major reasons that people decided to close the blind (Van Den Wymelenberg, 2012).

For environmental factors, high illumination level is not the main reason for shading device operation (Alrubaih et al., 2013). High illuminance is found to be tolerated until there is glare or impact from direct sun. Van Den Wymelenberg (2012) suggested avoiding glare as the most important reason for blind occlusion, especially when a computer screen is the main visual task. Rea (1984) stated that to prevent the room from receiving direct sunlight and thermal radiation are the main reasons for closing blinds. The study emphasized a greater frequency of blind operation for a clear sky than an overcast sky. Similarly, Theodorson (2009) stated that south orientations obviously required blind operation more frequently than north facing. According to Silvestre et al. (2009)'s survey, visual comfort has much higher impact on blind operation than thermal comfort.

Van Den Wymelenberg (2012) claimed that window orientation has the most impact on blind occlusion. It is agreed in many pieces of research in different climates that the blind was operated with the most frequency in south orientation and the least in north orientation. Season and sky condition are the other influential factors. Respectively, occupants needed to close the blind less frequently in winter and under an overcast sky. The operations were generally made in a period of weeks or months, rarely by days or hours. Findings of Rea (1984) supported less frequency of daily blind operation by stating that occupants rarely operated the blind within the day although there was significant change of solar radiation. Influence of direct sun may be investigated important but the cases of less occlusion in winter and during a day when the sun potentially located in low positions reveals that influence of direct sun may not be a curtain reason of blind closing as the blind was not closed every time it is direct sun. Penetration depth of sunlight was claimed to be a key factor. Van Den Wymelenberg (2012) suggested that the threshold of exterior irradiance measured normal to the sun at 120 W/m^2 and the range of exterior vertical illuminances between 20,000 lux and 100,000 lux are conditions that people might need blinds to be opened.

Automatic operating systems have been recommended in many studies: Inkarojrit (2005) for example whereas Alrubaih et al. (2013) shows the main problem of automatic system of blinds operation is that its operation frequency due to daylight fluctuation and improper integration of lighting and operating systems. The issues can bring about irritation and unsuccessful daylighting. The system was proved appropriated for office building while manual method is suggested for classrooms, according to rating systems such as LEED (USGBC, 2009) and BREEAM (BRE, 2011). However, manual operation was found difficult to occur as occupants rarely operated blinds, especially when they were closed (Rea, 1984). Apart from for privacy, the manual operation also depends on occupants' behaviour and perception for brightness. People probably have various perceptions for assessing glare and can tolerate different levels of light intensity. Moreover, in most discomfort conditions occupants appear not to notice serious problems. They normally do not design to change lighting conditions until it is difficult to see tasks or it there is disability glare. Operation frequency rates of automatic blinds was found much higher than that of manual systems but a lot of evidence which was reviewed by Van Den Wymelenberg (2012) who reported that occupants thought automated systems provided insufficient blind opening. These findings implied that users tended to open the blind less than are supposed to be for improving brightness. It might due to the fact that either occupants' satisfaction might be overestimated, or they decided to do nothing although the lighting environment is unacceptable. Additionally, occupants' familiarity in lighting environment possibly results in their visual comfort assessment. Boubekri and Boyer (1992) for example, users who commonly used no window space might overestimate their lighting satisfaction and operate the blind when the direct sun slightly affected the room.

Blind operation behaviour of classroom occupants appears to have very little frequency due to two main reasons. Firstly, occupants were much influenced by different lighting requirement of learning activities than fluctuation of natural light. Presentation equipment which has become one of the main visual tasks in recent classrooms required less illumination level. It results in more frequency of blind occlusion than opening condition which generally allows more daylight passing. Lastly, occupants appear not to notice or unintentionally accept improper lighting condition whether too dim or too bright environment. The blind for which occlusion is the default condition will hardly be opened unless it is extreme change of the daylight or new activity with different lighting requirement commence. Obviously, this behaviour is one of the key barriers for daylighting that needed to be solved.

To integrate artificial light, Steemers (1994) suggested that the set of light parallel to the main window wall should be required to switch independently. Switch options consist of on/off, stepped and dimmed systems which can be operated either manually or automatically. There are many kinds of automatic switch control such as timer, photo-electric, movement sensor and noise sensor. For energy conservation aspect, photo-electric dimming or stepped switch control appear to be proper for integrating with daylighting strategies as light level can be automatically increased whenever natural light transfers insufficiently.

The selection of lighting control systems also depends on the context of the spaces. For some irregularly occupied areas, such as walk ways, on/off automatic switch with movement sensor probably provides the more effective result in terms of total electric lighting load reduction. For more regularly occupied space, office spaces and classrooms were considered. Office spaces appeared to use artificial light for the entire office hours while classrooms were more frequently switching on and off light due to changes of activities, according to Hunt (1979)'s study in the UK. Apart from different behaviour of occupants, the use of lighting in the school classroom appeared to relate to daylight level more than the office space. It was found that office users even sitting near window positions usually applied lighting even though daylight level was sufficient. According to Steemers (1994), the application of a dimming system to personal control lighting switched was found canto reduce lighting load of an office for about 30% whereas over 60% of lighting load can be saved when utilising a centralised system. Diming control was found to probably increase total energy consumption unless automatic control of shading device was included (Yun et al., 2014). The dynamic control was suggested for all orientations and it was proved can achieve glare control.

For classrooms, Steemers (1994) suggested a centralised on and off timer switch to be the most proper solution as classrooms are generally operated by following fixed schedules. Ramasoot and Fotios (2009) argued that lighting operation like dimming control across classrooms is probably no longer appropriate for ICT classrooms. Rather than the controls that depend on daylight penetration, manual system appear more suitable because various visual tasks of the classrooms require specific lighting environment which should be controlled at the time that learning activities are switched. For manual control, the use of lighting also depended on daylight level in the room. For example, it is less in the morning when high level of daylight transferring. However, other factors have more impact on users' decision. Occupants' behaviour in lighting control was exemplified by Hunt (1979a) that occupants normally switched the light on at the beginning and off at the end of room occupation. They rarely operated the light between using spaces. The operation was either fully switching on or off. Although lighting switches were separated, partly application of the light appeared not a users' preference. In the case that overwhelming illuminance occurred, the occupants appeared not notice until it is serious effect such as disability glare, therefore, they almost never switched off the light during occupied the room. Although additional light on was required when inadequate light level on tasks and in general, occupants might not decide to switch on the light. Eye adaptation is possibly the cause but there are other important reasons why they did not improve room condition: to operate the light can interrupt working and disturb other persons.

Those findings reveal that although lighting layout is compatible to room functions, lighting control habits can cause an unsatisfactory light environment. Similar to blind operation, occupants rarely operate the light for various reasons. For classrooms, the most important factor of lighting improvement appears to be learning activities and equipment. Conflicts of required light level are lighting design difficulties. The difficulties can be more complicate when using the daylight; therefore, daylight was generally avoided instead of being enhanced. However, when a high light level was required, and daylighting can be of benefit, occupants either did not notice or accept an unsatisfactory light environment. For classrooms, teachers normally dominate the class. Winterbottom and Wilkins (2009) suggested that they should be facilitated to assess illumination level because occupants judged inaccurate illuminance or delay judging. Support system may be required to facilitate daylighting control.

2.5 Classroom environmental design

For studying façade design, it may be other related factors which influence occupants' sensation dominating their environmental comfort. For learning space, educational achievement is also important. According to previous research such as Montazami et al. (2015), holistic consideration was strongly recommended. Architectural design was confirmed can facilitate occupants' environmental comfort. Tanner (2000) presented influential design factors that related to students' learning performance: positive outdoor space, density and expansion, teaching technologies and overall impression of the learning environment. Other factors such as nature of classrooms and classroom occupants including other design element techniques should be investigated in order to understand overall problems.

1) Development of classroom design

According to review of daylighting history in school by Wu and Ng (2003), the school design guideline has been widespread implemented since mid of the nineteenth century. For good daylighting and ventilation, an idea of open-air school which contain large areas of windows was raised between 1900 and 1930. The additional window located opposite to the main window connecting to the corridor for ventilation aspect. As an advantage of typical one-story buildings which was common in the past, the transparent corridor roof and top window over the roof were applied for facilitated daylight delivering. These strategies can recently apply but in very limited circumstance. Because of expansion demand in present school, typical multi-layer classrooms have been generally applied.

For student concentration including avoiding occurrence of heat and glare, minimising window area with the replacement of artificial light subsequently became an idea to deal with visual comfort of classrooms. There is a research demonstrated that there is no significant different between classroom with or without window (Demos et al., 1967). A study in Dutch schools, Sleegers et al., 2012, probably supports that findings. Its results reveal benefit of artificial light environment on student learning performance. However, long-term studies affirmed importance of daylight (Larson, 1965) and view to outside (Stewart, 1981 and Tanner, 2000) for student health and learning performance. Daylighting and visual connection to the outdoors also have been recommended for High Performance Schools in California (CHPS, 2006). From Hathaway et al. (1992)'s to Hathaway (1995)'s studies, type of artificial light which is most similar to natural light was investigated more benefit to students' ecademic achievement and health. An idea of lighting control in windowless classrooms appeared not widespread applied might be due to the fact that unexposed spaces are not people preference.

Latterly, an idea of passive solar design was introduced in school (Wu and Ng, 2003). Classroom windows were oriented to the north. Additional window was assigned in the opposite side connected to the corridor. The covered corridor facing south can solve sunlight protection in summer then allow direct sun for heating in winter. Recently, Information and Communication Technology (ICT) has been introduced and become a new trend of classrooms especially in higher education. Its visual interface, such as Display Screen Equipment (DSE) and digital projector with front projection screen, is either self-illuminated or reflecting light visual tasks. Ramasoot and Fotios (2009) stated that these tasks require different lighting environments. Bright condition may be able to satisfy visual performance for traditional paper-based tasks, but ICT equipment requires dim environment which also hardly cause reflection problems. The study implied that even top lighting of artificial light which has been believed that have less problems in terms of reflection can also cause problems for the new teaching media. Window side lighting probably causes more complicated difficulties. According to daylighting study in multi-media classrooms in Thailand, apart from lack of uniformity and inadequate (Saihong and Srisutapan, 2007), reflection problems were also generally found (Tangpoonsupsiri, 2001).

2) General characteristic of classrooms

In general, school buildings have been designed in various types from simple plan like single contiguous classrooms to complex shapes such as atrium. Their typical elements consist of classroom, classroom windows along room width and corridor for accessing the classrooms in the opposite side. The corridor can be opened, closed or exposed to atrium or open court. Therefore, there are two main facades that can be improved for daylighting. Façade on the window side obviously has been used as the main daylighting source while it is just access for the corridor side. Due to its narrow plan and large opened area, daylighting alone is adequate for corridors during working hours (Li and Lam, 2003). As well as the daylighting performance of atrium, Chow et al. (2013) comfirmed the efficiency of the atrium and illustrated differences of average illumiance by orientation and floor level. The finding of these studies imply posibility of using corridor side façade to be an additional daylight souce.

Classrooms contain various sizes, types and equipment. In a typical style 50-60 seat classrooms appear to be common in university lecture room in Thailand. This size also can be found in large middle and high schools in general. According to the Office of the Basic Education Commission of Thailand, a standard size of 50 seat classroom is recommended to be at least 7 metres wide by 9 metres deep by 3.2 metres high (Tangpoonsupsiri, 2001). With the standard size, Tangpoonsupsiri (2001) applied a 1.2 metre height window which lifted 0.9 metre from room floor with 0.6 metre height top window along the width of the room to be general appearance of rural classrooms in Thailand. In the Faculty of Architecture, Urban Design and Creative Arts, Masarakham University for example, the most common classroom size is typically 8m x 10.5m x 3.4m in height for 60 seats. Similarly, Saihong and Srisutapan (2007) stated that the most common size of lecture room in Thammasat University, Bangkok is 50 seat classrooms. The rooms are approximately 9m x 11m x 3m high, including a continuous window at one side of the room. The window was lifted about one metre from the room floor and ended at the room ceiling. The narrow proportion of the classrooms probably causes problems in terms of daylighting and visual difficulty. Apart from substantial decrease of daylight level in the further area from window, students who sit at the further sides in front rows possibly hardly see tasks at teaching area located in the mid front of the room.

Traditionally, classroom windows have been recommended to be located at the left side of the students' lecture desk in order to avoid hand shadow on task when taking note. However, there is no empirical evidence that confirms this belief, and it is possible that its influence may be insignificant. Denan (2004) defined assessment of visual task performance that subjective and related to brightness contrast and glare. For seat orientation, the researcher reported just window facing seat can cause visual discomfort. Other seat orientations have no problem in general although there is excessive high window luminance. The result is noted that as the study was obtained in Malaysia, occupants probably preferred brighter conditions than standards that generally originated from western countries. Boubekri and Boyer (1992)'s study obtained in USA supported this findings by stating that if windows locate on any side of observers, it will hardly cause glare although direct sun affect the room.

The front of the classrooms generally is the teaching area, consisting of the teacher's desk and vertical seeing tasks on the front wall. The wall may contain notice boards and a writing board. White glossy materials have been usually applied specially for higher educations. Apart from whiteboard, types of projectors are normally used with projector screen. Consequently, classrooms contain three visual tasks: projector screen, whiteboard and lecture desk. Artificial light might be controlled either by one switch or separately. For cost saving, lighting layout is generally depended on daylighting although separated systems by window and teaching area has been recommended.

3) Classroom occupants

The occupants of classrooms consist of a teacher and students. Naturally, teachers rule all teaching activities, for which a good lighting environment is required. Students may have the opportunity to control during break time or when there is no teacher but needs of light level for those times are much more flexible. De Giuli et al. (2013) found that not only classroom conditions depend on teachers, but students also yield the conditions. For discomfort conditions, Boubekri and Boyer (1992) rather claimed that students appeared to have less tolerance than teachers. It might result from their positions were nearer to the window than teacher's. They probably were influenced from outside disturbance such as direct sun and noise.

When considering their comfort, the occupants will express their discomfort only if there are extremely unfavourable circumstances. For example, they complain about visual and thermal discomfort when the direct sun influenced their classroom. Boubekri and Boyer (1992) stated that they emphasized their visual proplems more than thermal aspect. Montenegro et al. (2012) pointed out that high quality of lighting was strongly required in classrooms as there are various luminance levels on different visual tasks that students must see in the meantime, conflict of lighting environment for paper task and projector screen for example. Higher levels of illuminance are requires for paper task. For ICT visual tasks, Ramasoot and Fotios (2009) suggested three criteria: *disturbance*, *contrast* and *clarity*. *Clarity* was ranked to be most significant while *disturbance* was the least. It reveals that quality of the equipment may dominate performance of the task more than lighting environment. Quality of the equipment then can be another influential factor that has to be considered.

The age of students leads to differences in terms of behavior and preference. Young students naturally can be more distracted than adult students. Fisher et al. (2014) exemplified previous research that outside view has insignificant impact on students' attention and task performance in elementary school whereas highly decorated visual environment can distract kindergarten children and have negative effect on their learning performance. Tennessen and Cimprich (1995) supported this result by stating that natural views were affirmed resulting in better performance on older students' attention. The findings imply that outside view can advantage adult students rather than distract their study.

4) Other design suggestions

Apart from façade design, other general suggestions for classroom daylighting such as room proportion that should not be much narrow and room reflectance which was recommended to be high are already mentioned because it influences façade design parameters. Three case studies that focused on room design parameters will be illustrated in this part representing the rest of suggestions for classroom daylighting design.

The design of D'Hautree School, a secondary school in Jersey, Channel Islands aimed to produce low energy while gain high quality of environment (Steemers, 1994). The school buildings were designed to be arranged in clusters with landscape design in order to maximise daylight illuminance in winter and shade direct sunlight in summer. For daylighting, the design team finalised their classroom design to be shallow plan with high curved ceiling. While six metre depth has been suggested for daylighting the room, the school rather has typical depth at seven metres with integrations of window above eye level one and additional window for daylighting from corridor. While general schools solve only 50%, this school tended to achieve daylighting at 95% of learning areas. It is 70% of energy cost can be reduced in estimated. However, energy cost may be significantly reduced but the application of high and curve ceiling is also costly. In addition, the room depth is just a little higher than general recommendation leading to not much effort to improve light environment of the classrooms.

Intarakulchai (2013) focused on design solution for improving drawing studios in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University, Thailand. With 12 metre depth facing northwest, its main problem was inadequate daylight illuminance. In order to deal with the difficulty, the researcher suggested four strategies: ceiling finishing addition, internal walls removing, refurbishment for opposite side windows and light pipe system integration. Unexpectedly, the additional window and light pipe provided no significant difference. According to the researcher, the issue probably resulted from incompatibility between effected and occupied time and ineffectiveness of the device. Addition of reflective ceiling and displacement of internal walls was proved can improve illumination level and uniformity ratio. Unfortunately, although light environment of the studios was improved, it never met the standard of 700 lux. It is noted for this research that not only using higher illuminance threshold than lecture room but also reporting too rough results. Greater than 300 lux illuminances were predicted from suggestion models. The lighting level may satisfy if the room function is lecture room. However, the use of annual room average values in the research may not be able to show variation of room illuminance and differences of daylight distribution when time and season change. Therefore, the average should not be generalised especially for tropical zones where sun geometry has much more influence.

Studying visual comfort in classrooms in rural area in Thailand, Tangpoonsupsiri (2001) suggested designs of inclination of ceiling, windowsill, glazing, white board and lecture desk top with window located at the back of the room. In this window position, only teacher can face glare problems. Combination of tilted ceiling and windowsill can facilitate daylight delivering leading to higher illuminance at the further area from window. A 15º tilted-out glazing was proved that can reduce effect of high intensity light from the sky on teacher's eyes. The application of a 5º tilted whiteboard and lecture desk can solve reflection problems by avoiding reflected glare and veiling reflection. However, the negative effect of the window position has not been mentioned in this study. Working plane illuminance will be decreased if students occupy the room. The back window may avoid the effect of glare on students but according to Boubekri and Boyer (1992)'s study side windows already provide less possibility of glare occurrence. Inclined elements design may be effective solutions, but its construction needs more budget and technical skills. Moreover, the suggested degrees can be questioned since a fixed degree was suggested while the sun is dynamic.

2.6 Reflection strategies

Although the reflection strategies have been confirmed as being less significant in terms of thermal aspect, it is usually suggested not to exclude them, as they are one of the most important parameters for daylighting. Consequently, reflecting strategies is the additional parameter for this study.

1) Principle of sidelighting

For wall-based sidelighting design, internal horizontal illuminance relies on effects of both sky illuminance and reflected illuminance from the ground. Theoretically, all factors are shown in equations 2.6 and 2.7:

$$Esp = [[Esv * CUs] + [Egv * CUg]] * Agl * Tgl \quad (2.6)$$

where E_{sp} = Station point illuminance

E_{sv} = Vertical illuminance from the sky

CU_s = Coefficient of Utilization from the sky

E_{gv} = Vertical illuminance reflected from the ground

CU_g = Coefficient of Utilization from the ground

A_{gl} = Glazing area

T_{gl} = Glazing transmittance

$$E_{gv} = R_g * \text{Field proportion factor} \quad \text{(2.7)}$$

where E_{gv} = Vertical illuminance reflected from the ground

R_g = Ground reflectance

Source: Simplified from LIBBEY-OWENS-FORD COMPANY, 1976: pp17

Apart from windows area and glazing transmittance, the influence of interior reflectance and room size ratios can be significant factors. According to equation (2.7), the effect from the ground depends on the reflectance of the ground Supansomboon (2002) investigated the impact of the reflectance on sky and ground component in a tropical climate, Thailand. Different window positions and ceiling heights result in different impact of ground reflection (Figure 2.12).

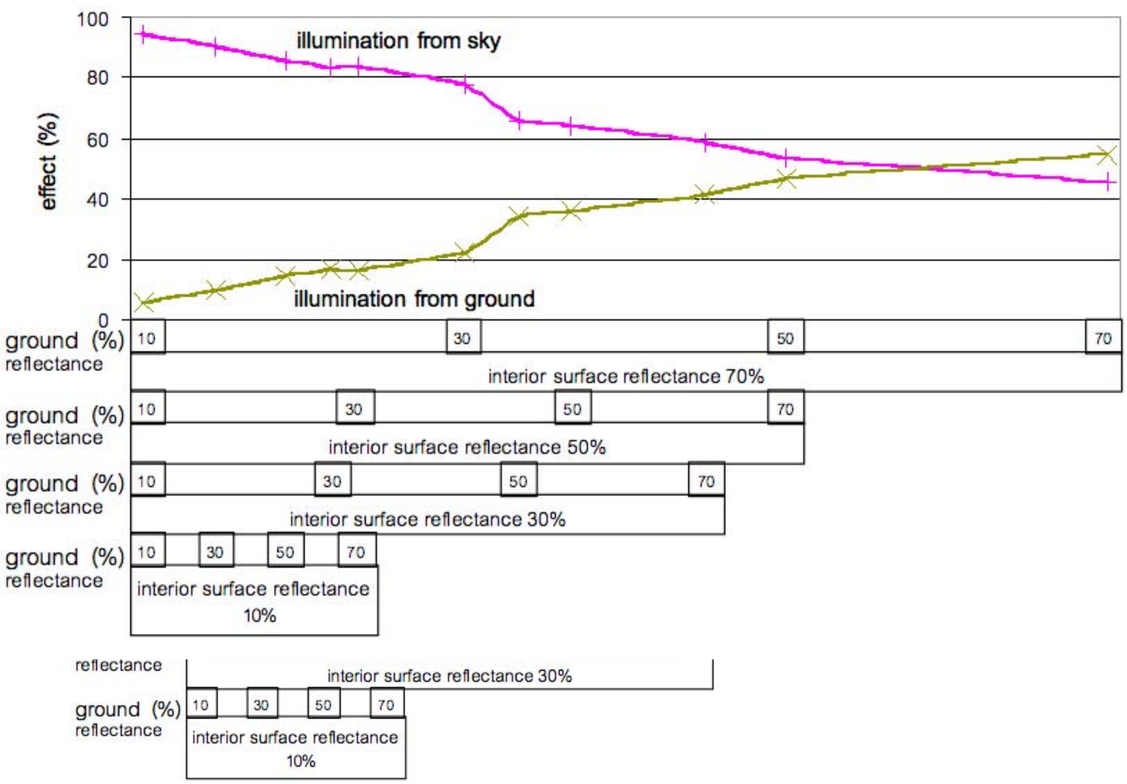


Fig.2. 12 Relationships between reflectance and impact of sky and ground illuminance for sidelighting

Source: Supansomboon (2002)

When the field proportion factor is 0.5, illumination from the sky has more affect on working plane illuminance than the effect from the ground in most cases. Only a ground reflectance more than 60%, with a 70% room reflectance, can cause the ground to have a higher impact. When the proportion of a reflecting plane is considered, the plane is required to be closest to the window bottom. The ground proportion should be enlarged when the plane is located far from the window. As shown in Figure 2.13, less proportion of the ground only effects on 'low window' while the large areas of the reflective ground obviously benefits 'view window'. The maximum ground field proportion can improve daylight factor for 1.5-20%. For reflective ground or other types of reflecting plane, this proportion might be impractical in the real situation. However, the 12.5% of ground proportion which is 0.6 metre depth probably increase little DF at about 0.25%. The depth of 0.6 metre appears to be possible for applying as light shelves.

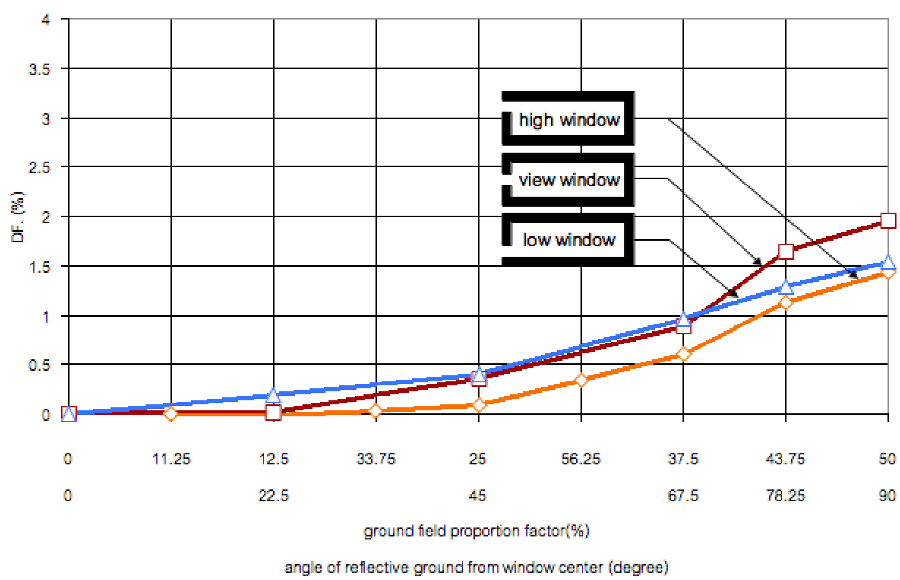


Fig.2. 13 Increasing daylight factor in different ground field proportions and window positions.

Source: Supansomboon (2002)

2) Effects of sky conditions

Supansomboon (2002) reported some interesting results, in which more specific reflecting elements were investigated (Figure 2.14). With the same reflectance, glossy surfaces may have a lower impact on room illuminance than matt surfaces in general, but they provide more illuminance when altitudes of the sun are small. The small angles not only affect the room average DF but also have a high impact on the furthest area from the window. As another advantage of glossy surface, half size of the reflecting devices causes only little difference illuminance comparing to the 50% field proportion.

Apart from combination of surface and sun altitude, the previous study revealed that not every daylighting methods have positive effects on reflecting strategies; top window and high ceiling, for example, are also important. Reflection from the ground influences high window and high ceiling less than lower window and normal ceiling height respectively. The reflecting methods will be more efficient for daylighting when general window position and ceiling height are applied.

The findings of Supansomboon (2002) may also be applied to other types of horizontal plane such as light shelves. To sum up, the reflecting planes can be one of the most effective strategies for sidelighting design to be used with a reflective room interior. Lim and Ahmad (2015) also found very similar results in their scaled-model illumination measurement in Malaysia. Using aluminium light shelves, the research confirmed the effectiveness of a reflective glossy surface when it is low angle sun. The low angle sunlight can most improve illuminance at the furthest area from the window, resulting in more uniform room illuminance. Without direct sun, light shelves perform poorly. The illumination levels are low, even when compare to overcast sky.

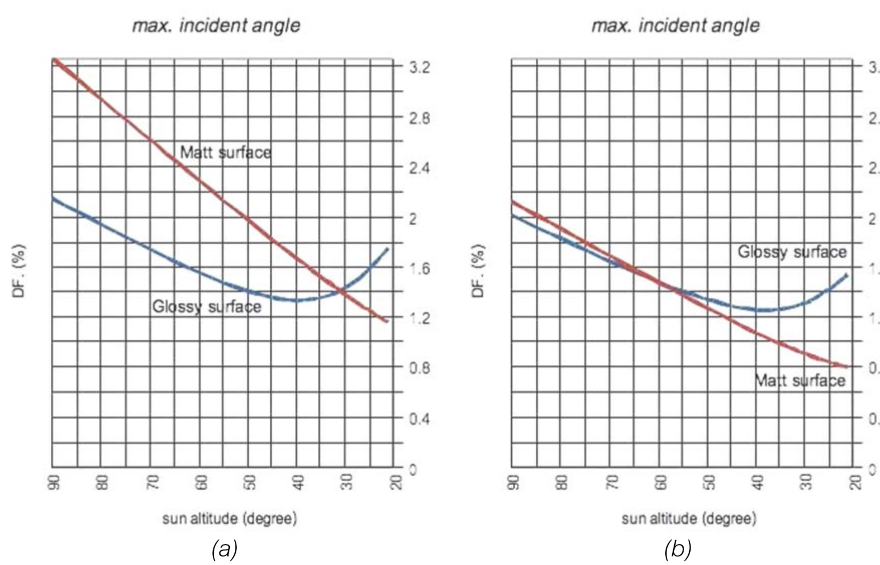


Fig.2. 14 Average daylight factor of rooms with effects of ground surface in different vertical shadow angles (a) Room average and (b) Average of the furthest row from the window

Source: Supansomboon (2002)

According to a literature review by Freewan et.al. (2008), sunlight was confirmed necessary for reflecting devices. Because the review aimed to show importance of light-shelf application for daylighting in tropical and sub-tropical skies using previous studies obtained in sub-tropical and temperate climates, the generalisation can be questioned. Because of different-latitude locations, sub-tropical and temperate climate skies are normally influenced by low angle sun, which benefits light shelf performance while sun altitudes are generally approximately vertically overhead in tropical sky. It should be noted that reflecting strategies might benefit daylighting in sub-tropical and temperate climates more than in tropical climates. In other words, application of light shelf in tropical climates probably increases smaller amount of illumination level in general. Moreover, the fact that the devices cannot always improve the illuminance in the rare of the room for those higher latitude areas reveals much poorer performance of light shelves in tropical climates.

3) Design suggestions

Based on research in a tropical climate, Kakham and et. al (2010) claimed that horizontal louvre blinds are more appropriate for using with natural light than vertical blind as the devices not only can better control excessive high levels of illumination but also improve uniformity of working plane illuminance. The result reveals positive effect of horizontal devices, which not only can control excessive high illuminance but also reflect the daylight to deeper part of rooms while the diffuse transmission components of the devices can only control the daylight.

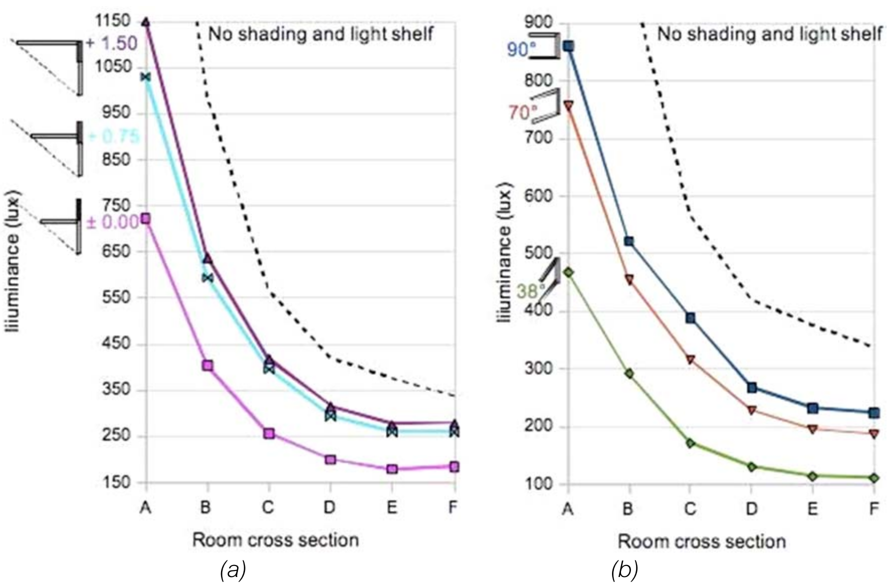


Fig.2. 15 Average illuminance of shading types (a) different shading positions and (b) different angles of shading and reflecting blades. Source: Supansomboon (1998)

Investigating the impacts of shading types, Supansomboon (1998) found that for the same vertical shadow angle the higher position of a shading device can provide better results for an overcast sky (shown in Figure.2.15(a)). With a light shelf (Figure.2.15(b)), the horizontal type performs best compared to tilted blades.

The results in Figure 2.16 partly agree with previous studies from David et.al. (2011) and Chou et.al. (2004). For the parallel horizontal devices, the blades are recommended to be small in terms of both size and number. The graphs also report importance of the light shelf at the window bottom. Illumination levels of all graphs in Figure.2.16(b) are higher than those in Figure.2.16(a). The fewer blades provide the better results in general. The device with small shading and light shelves at the bottom of top and main windows provides maximum illuminance at the rear of the room.

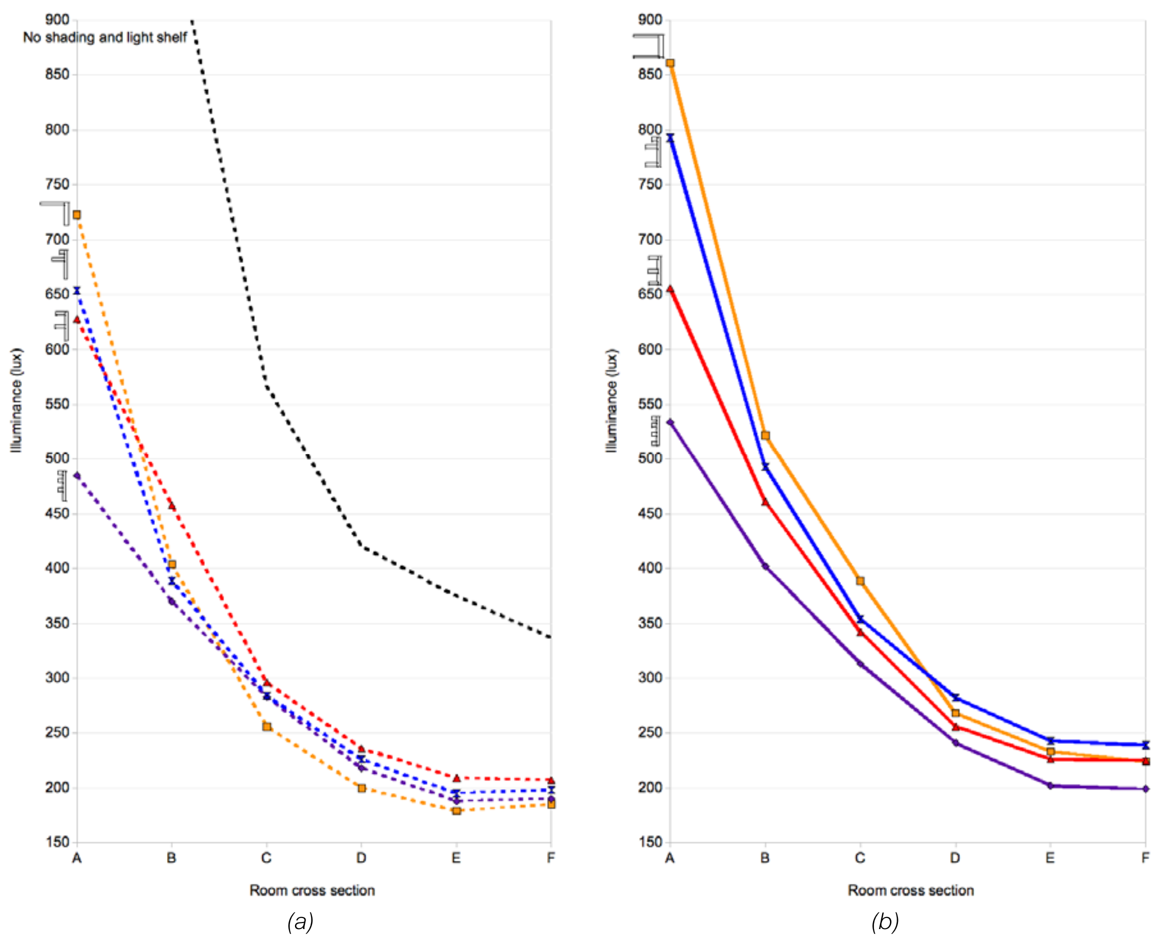


Fig.2. 16 Average illuminance of shading and reflecting devices (a) without and (b) with light shelf at the window bottom. Source: Supansomboon (1998)

More specific suggestions were made by Lim and Ahmad (2015), who obtained their physical scaled model measurements under tropical sky. Due to variation of sky conditions, adjustable light shelves shown in Figure,2.17 are recommended instead of specific design for each window orientation. When a set of two 300mm wide internal shelves horizontally divided a window space into three equal areas as the light shelves for intermediate sky without direct sun, the lower light shelves suited the intermediate sky with a low angle sun. The lower shelf is suggested to be smaller for the bigger sun angle and it is not required for an overcast sky. The effect of the lower shelf under real overcast sky of Lim and Ahmad (2015) slightly differs to Supansomboon (1998)'s results which were measured under artificial sky. It can be implied that the devices for overcast skies are required to contain a top light shelf with less obstructed blades; however, the window-bottom blade is excluded because it only advantages daylighting in the same direction as positive effects of ground reflection found in Supansomboon (2002).

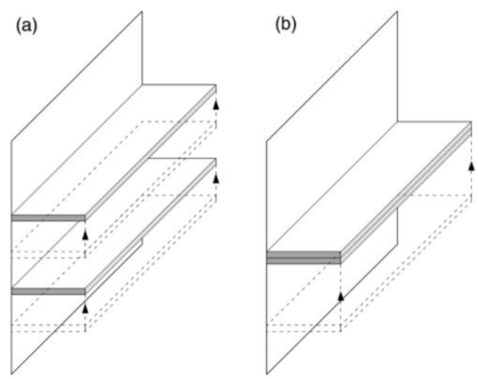


Fig.2. 17 Suggested solutions of adjustable light selves from intermediate sky without direct sun to (a) intermediate sky with low angle sun and (b) overcast sky. Source: Lim and Ahmad (2015)

Integrating the results according to Figure 2.15 and 2.16, Supansomboon (1998) examined illumination levels with shading applications in which the device distance, reflective blades and window-bottom light shelf were included. It can be concluded using the results in Figure 2.18 that the higher and more distant the devices from the window then the better the daylighting result. When the devices were lifted above the window top, there are very slightly different illuminance patterns between the blind shades, horizontal and tilted bladed. Moreover, the devices can reduce only little amount of illumination at the furthest area from the window. The results reveal more significance of non-obstructed devices over the mid reflecting device, which has been believed one of the best solutions that should be intensively investigated.

The effect of classroom facade types on daylight levels, obtained in an artificial sky are shown in Figure 2.19. According to Aghemo et. al. (2008), the solutions that can provide best illumination uniformity are 'Horizontal Fins' and 'External Light Shelf' respectively. The study shows ineffective application of internal light shelf that may increase illuminance at the back of the room but cannot reduce excessive high illumination level near window area. In the case where an internal light shelf was combined to external light shelf, the external device can control the daylight at the window area while the combination cannot provide more illuminance and the furthest area comparing to the case without reflecting device. The result appears disagree to Supansomboon (1998) as the best solution is the case that contains most blades but it also can confirm importance of lower light shelves. However, concordant results in different sky conditions of the study can be questioned. Because the results were obtained not only in low-sun-altitude area but also under artificial sky, the effect of direct sun can be impractical for tropical skies, where the solutions of Lim and Ahmad (2015) may be better.

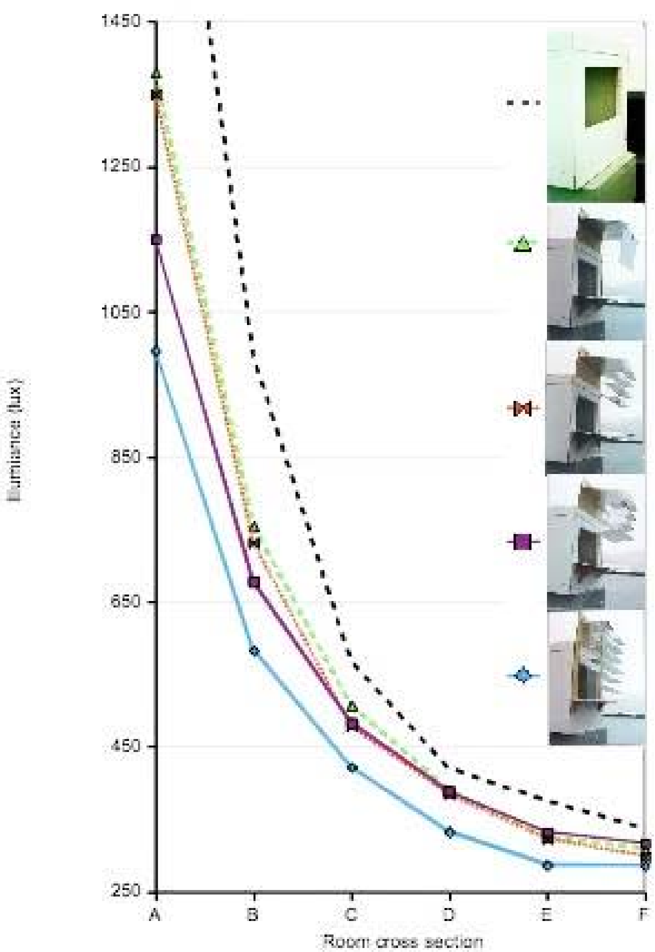


Fig.2. 18 Average illuminance of applications of Supansomboon (1998)'s findings

Source: Supansomboon (1998)

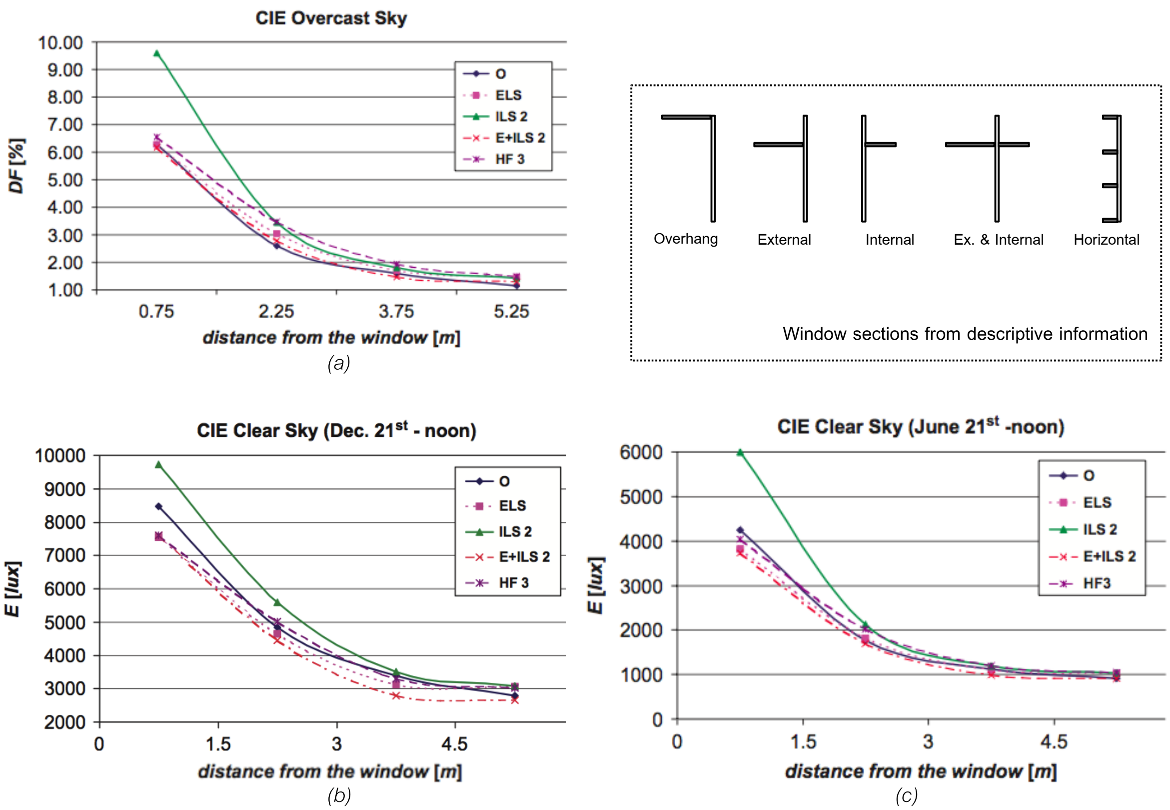


Fig.2. 19 Daylighting performance of different types of shading devices in classroom in Italy under (a) overcast sky, (b) December 21st and (c) June 21st clear sky

Source: Aghemo et. al. (2008)

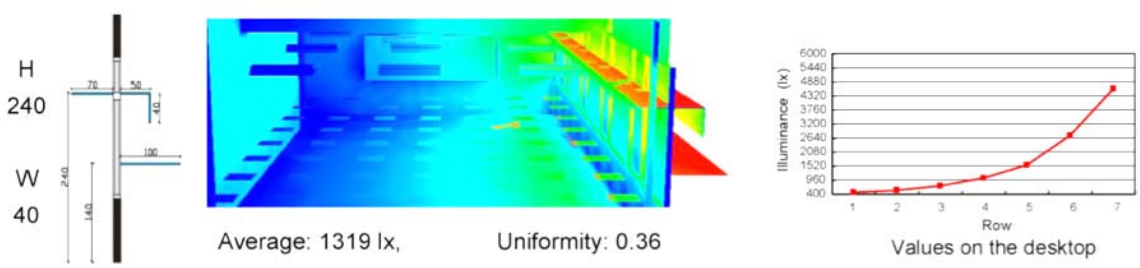


Fig.2. 20 The suggested solution in a study in a subtropical climate, Taiwan.

Source: Ho et. al. (2008)

Ho et. al. (2008), who calibrated their simulations with real classroom measurements in a sub-tropical climate, reported that an external light shelf and the combination of external and internal light shelf failed to improve illumination uniformity especially in cases with the device located lower than the vertical midpoint of the window. Combinations of top ex.-internal light shelf with vertical element and low light shelf (Figure 2.20) are suggested as the most proper solution in terms of uniformity. The suggestion provides less illuminance in general but the average illuminance in the furthest area from the window was confirmed to meet the standard of 300 lux. However, when daylighting was considered hourly, there are some cases that the minimum illuminance is lower than recommendation. The addition of artificial light is recommended for those cases.

Although located at a higher latitude, the suggestions of Aghemo et. al. (2008) and Ho et. al. (2008) partly agree with the study of Supansomboon (1998); Supansomboon (2002) and Lim and Ahmad (2015) in terms of suggested shading and reflecting planes. It can be concluded that not only a top horizontal device is required for controlling the excessive high illuminance near window area, but also a low light shelf is recommended to be included for increasing the illuminance in the furthest area from the window. However, the study of Supansomboon (1998), Supansomboon (2002) and Lim and Ahmad (2015), which were obtained in tropical climates, reported considerably less illumination levels than the results from higher latitude area like Aghemo et. al. (2008) and Ho et. al. (2008). A distinctive effect of low angle sun on horizontal reflecting planes in tropical sky found by Supansomboon (2002) and Lim and Ahmad (2015) reveals the need of different strategies. In tropical climates, low angle sun rarely happens in working hour and, therefore, the benefit of reflecting strategies can be less than that in subtropical and temperate climates.

Chapter 3

Methodology

To examine daylighting design guideline, two main methods have been applied: occupants' satisfaction survey and lighting assessment of design solutions. Lighting quantity can be assessed by measurement and simulation technique while satisfaction must be examined by asking the classroom occupants. In this chapter, applications and combinations of the three main techniques will be presented.

3.1 Three stages of study

In order to achieve research aims finding daylighting solutions for classroom façade in terms of qualitative and quantitative, three stages were set: problem monitoring, solution suggestion and application stages. Figure 3.1 shows diagram of the three stages of the research including their methods.

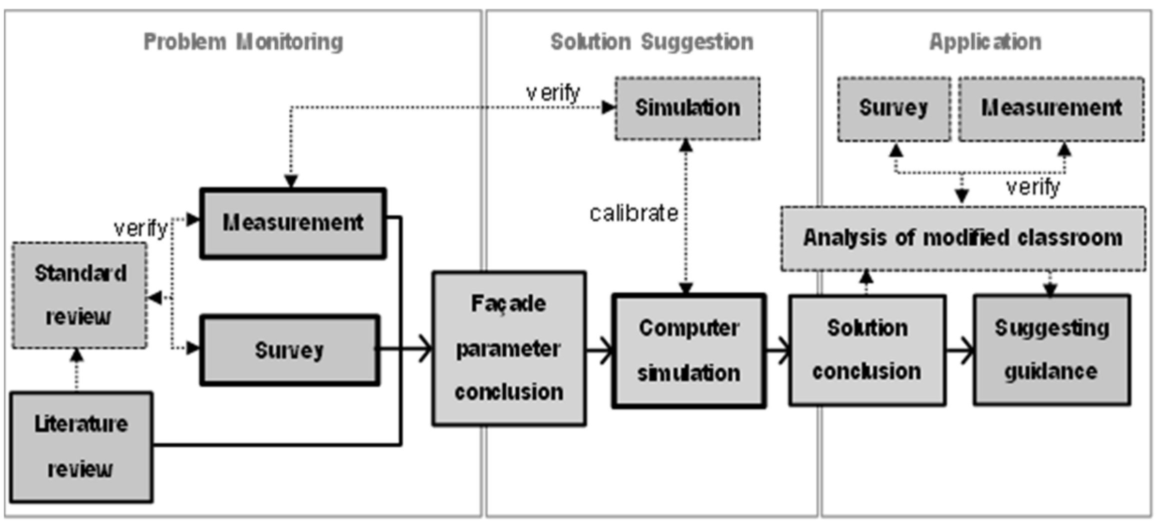


Fig.3.1 Diagram of the three research stages

The first stage, *problem monitoring*, were assigned since the more understanding of problems the better it can be solved. Using an Idea of Post-occupancy Assessments (POE), it has been believed that each building has its own specific problems and the assessment after it was already operated is necessary for solving those problems (Halliday, 2008). Occupant satisfaction survey comparing to real use monitoring was affirmed practical for design improvement (Barrett et al., 2013). In this study, the classroom façade issues specific in daylighting was investigated using three methods which are previous research study, occupants' satisfaction survey and the real use monitoring consisted of physical measurement and class observation. Previous studies not only can provide general problems for daylighting in classroom, but differences of specific issues also can benefit the recent study when causes and results of them are discussed. For studying specific problems, to ask regular users' opinion is most important. Their visual environment satisfaction and attitude in daylighting are focused. However, people opinions can be subjective. Observation of occupants' behavior and physical measurement therefore were required at the same time. Moreover, the concern regarding practicality of lighting standard can be solved in this stage. Verification of the standards can be made combining occupants' survey and measurement simultaneously. Major problems of the case study façade were concluded in this stage. Then, influential parameters were raised in order to apply for simulation stage.

For *solution suggestion*, the main method applied is computer simulation. The influential parameters concluded in the first stage are applied in this stage to investigate priority and relationship between each other. Since the research focused on both lighting and thermal predictions, the selected package was DesignBuilder. The result was verified using physical measurement at the real classrooms. Indicative guidance of façade design such as suggested size of elements is expected outcome of this stage.

Application stage is an additional process which was raised in order to verify practicality of some solution which was suggested from the previous stage in terms of visual comfort. Modify classroom was set in the case study building for obtaining the occupants' visual satisfaction and physical measurement, similar procedure to what had been done in the first stage.

The suggested solutions were applied to other classrooms in separate sites in order to generalise the findings. Before suggesting guidance, related strategies were integrated for including more suggestion. The classroom façade design guidance which is the research goal was suggested at the end of this stage.

3.2 Case study

As the case study of this research, the Faculty of Architecture, Urban Design and Creative Arts is an educational building belonged to Mahasarakham University, a public university in Thailand. The university was established about 40 years ago. The buildings in the university were designed separately. Their first concepts did not approach to environmental design. The case study is the first building of the university that the design may not intensely use an idea of green building, but the idea was rather concerned after the building was operated. About five years ago, Mahasarakham University implemented the green campus policy. The actions of the faculty and the university therefore provide opportunities for sustainable projects including research and application of building environment. This study focuses in specific classrooms in Faculty of Architecture, Urban Design and Creative Arts. The general information of the building will be presented in this section.

1) Building

The case study located in Mahasarakham, a province in the northeast of Thailand. As can be seen in Figure 3.2, the area is on the north hemisphere in middle latitude of tropic of cancer zone. Therefore, its climate supposed to be average between zoning edges which adjacent to equator and subtropical zones.

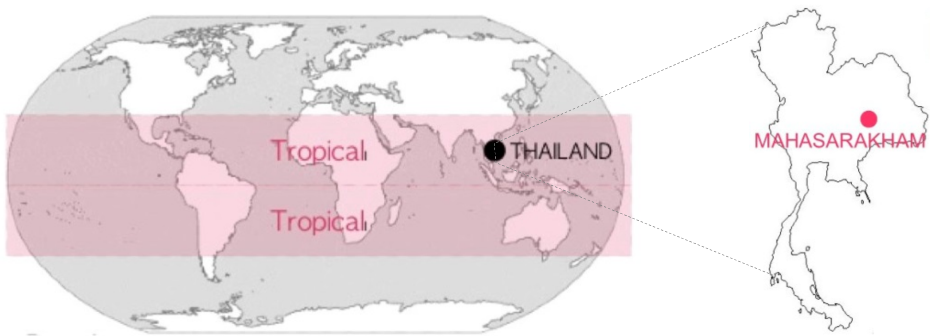


Fig.3. 2 Position of Mahasarakham province on world map and map of Thailand.

The building was established for a decade in Kantarawichai campus where size and form of faculty buildings were regulated to be the same: four to seven floors in square shape with central open court (the campus layout shown in Figure 3.3). Its coordinate is 16.43ºN 102.83ºE. The building approximately orientated to ordinal directions: 36º rotated clockwise from the north to south axis. The building site located in the northwest of the campus centre. The southeast orientation faces to greenery space and walk ways which connect to the main library. It is a large quarter circle shape concrete pond in the northeast. Buildings in the northwest which appear to be the nearest surroundings are sculpture workshop and faculty of Fine Arts building. Southwest orientation connects to the main walk way of the university which is a large open space with trees along the walk way.

There are three groups of building users. There are students, lecturers and administration staff. The largest group is students who involved with all class room the most. They can be categorised in to four departments: architecture (AR), urban design (UD), interior architecture (IA) and creative design (CA) consisting of five years of students in the first three departments and four for the latter. They are approximately 1,100 students in total. Basically, they use their own studio which located on the upper floors as their common areas. The lecture rooms are sharing spaces mainly operated by following classroom official time table. Apart from the use in time table, the rooms are frequently occupied for pin up or presentation purpose. Lecturers are about 40 in amount. They may not involve with space as much as students because they own other spaces but they the major person who influence the use of rooms. About 20 persons of administration staffs are definitely not classroom users. Excluding house keepers, it is not more than four staffs that are in charge of room operation and maintenance.

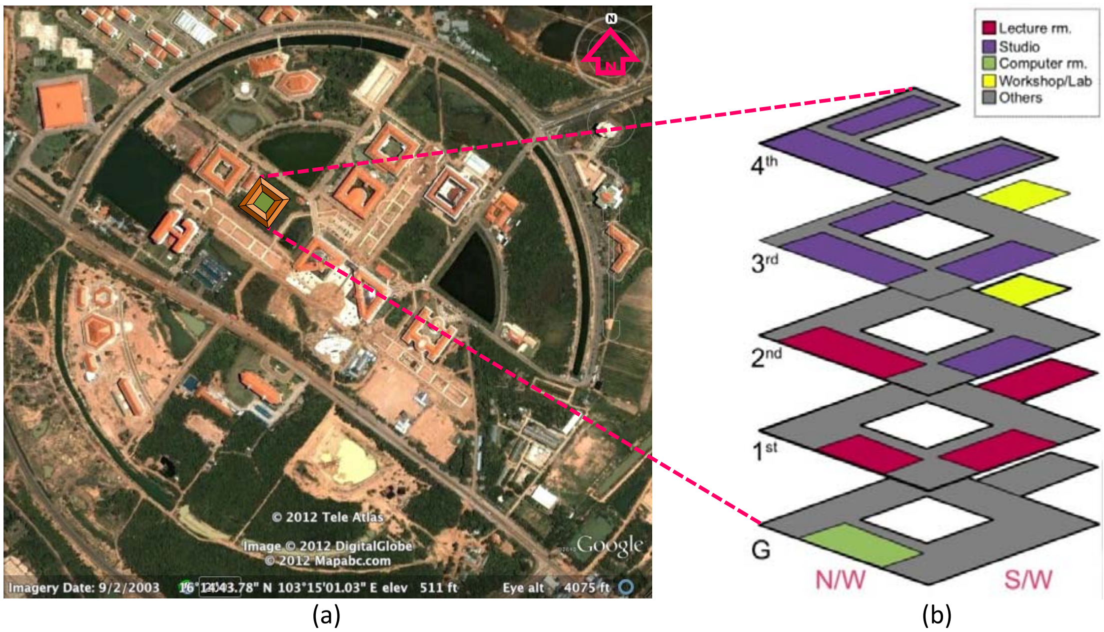


Fig.3. 3 Faculty of Architecture, Urban Design and Creative Arts: (a) position of the building on a layout map of Mahasarakham University, Kantarawichai campus and (b) diagram illustrates zoning of building functions.

Source: (a) Modified from Google Earth and (b) author

Actually, the faculty was moved from another building after ten years to this new building. The users who ever experience the former building are only a half of teachers and staffs. For most users, this building is their first and only building that they take part in. In addition, all of building architects are or used to be faculty lecturers who supposed to understand nature of users very well. As a result, the building users tend to have positive attitude for the building in general.

Functioning for educational purpose for architectural and designing students, the building contains many types of classrooms in common on its five layers. There are lecture rooms, drawing studios, computer classrooms and workshops. The focused type, lecture rooms, is generally located in southwest and northwest orientation on the first and second floors.

2) Classrooms

In this research, classrooms stand for only lecture rooms. Lecture rooms of this building located on the first and second floors various in sizes and orientations (details shown in Table 3.1). Due to their group size, the junior students normally used large rooms while the senior generally occupy smaller rooms. According to official time table of the classrooms, operated time of the classrooms is during 9AM to 12PM and 1PM to 4PM. The hours can be extended to 8AM and 5PM but it is rare. The operating hours of the classroom reveal that the rooms are generally occupied in the afternoon. All support systems: consisted of air conditioning system, artificial lighting, façade operation and teaching media are working separately for each room.

Tab.3. 1 Information of lecture room in the faculty building.

No.	Name	Orientation	Window		Floor	Amount (rooms)	Capacity (persons)	Main users
			Amount	Position				
1	Auditorium	South east	None	-	1st	1	240	Junior/ mixed department
2	AR204-208	Southwest	Single side	Right side of the room	1st	5	60	Senior/ AR or UD
3	AR213	Northwest	Single side	Back of the room	1st	1	100	Senior/ AR and UD
4	AR214	Northwest	Single side	Left side of the room	1st	1	150	Senior/ AR and UD
5	AR311-315	Northwest	Single side	Left side of the room	2nd	5	60	Senior/ IA or CA
6	AR316	Northwest	Single side	Right side of the room	2nd	1	150	Senior/ AR and UD

As shown in the table, the most regular size of classrooms of this building is 60 seats. The size is similar to the size of other university classrooms (Saihong and Srisutapan, 2007) and standard size of high school classroom (Tangpoonsupsiri, 2001). In this type of classrooms, students in AR and UD department generally study in the southwest lecture rooms on the first floor in general while it is the northwest classrooms on the second floor for IA and CA. For this type, all classrooms were generally observed while majority of occupants were asked. There are only the students in the first year who just commence their study that are excluded.

The specific rooms that were selected to be the case study consisted of the base case, comparative cases and modified classroom. AR 206 located in the middle among classrooms in the southwest on the first floor was applied as the case study base case. The room was always set in normal condition: opened curtain, off light and on air conditioning system. The comparative cases are similar rooms in various positions. AR205 and AR207 are next to the base case while AR313 is in the middle of classrooms in the northwest on the second floor. Different conditions were applied to the rooms in order to compare impact of existing façade system: window orientation, overhang, curtain and artificial light. In the final research stage when adaptable space is required, the exhibition room on the ground floor is available. Spaces on ground floor are generally lifted 1.2 metres from the ground. The room locates under classroom in the southwest with the same depth but about third wide of the regular classrooms. It is 0.4 metres higher than regular rooms. The space was enclosed with two opposite opaque internal walls and two opposite fully glazed walls connected to outside and corridor. The space can be divided using floor-to-ceiling height exhibition panels.

3.3 Focused parameters

According to literature reviews there are influential façade parameters mentioned. Differences of weather by time and season change have to be investigated in order to perceive daylighting availability of the case study. For design, the parameters consist of façade elements. Other influential factors are daylighting systems and its operation. The parameters may not façade design parameter but the grate impact of them is compulsory. Generally, impact of facade design elements can be investigate using simulation technique while influence of existing feature and operation of façade and lighting systems requires occupants' survey.

1) Time and season

The focused time for this study is the classroom working hours from 9AM to 4PM. The results may be obtained more frequently than hourly due to the fact that observation needs most intensive study, but it was averaged to be hourly for conciseness. Consequently, there are eight time slots required for every case.

For season, the season representative dates: winter solstice, summer solstice and two equinoxes; were applied including the dates that the sun is directly overhead which stand for the hottest date. All alternatives were analysed for six specific dates: 22nd of December, June, March and September; and 27th of April and 5th of May. When predicting stage was considered, there are six dates with eight times which is 48 repeats in total for each case. For the field study, the summer and winter solstices were selected, representing the minimum and maximum range of solar movement. Field studies are costly and time consuming, and so choosing these dates covers, theoretically, the range of conditions.

2) Façade feature

According to previous research, influential façade parameters for both daylighting and thermal aspect consisted of window area, shading device, window orientation and glazing type. Glazing type is excluding in this study because of two key reasons. Firstly, it is lack of impact on building appearance and can be changed with not much effort in every stage from design to refurbishment. For this reason, it can be investigated in further study. Lastly, the glazing selection depended on other criteria such as cost and maintenance issues. Good materials may advantage daylighting but are probably not feasible for government building in local areas. On the one hand, although proper glazing is specified, it can be the first priority to be excluded during the cost control process. On the other hand, the replacement of glazing can be considered later from construction to refurbishment. Therefore, glazing type is fixed to be clear glass when studying the other parameters: window area, shading device and window orientation. According to the physical measurement during summer solstice the results reveal lack of daylight availability due to the great depth of the rooms. For this reason, the existing window was raises to be the smallest window and window in the opposite side, the only feasible side, is included. For window area study, there are four focused cases: without window, existing window, fully glazed wall and two opposite fully glazed walls. Additional cases: opaque walls and a fully glazed wall at the corridor side; were applied for investigate influential of the opposite side window. The summary is shown in Figure 3.4.

a. Window area

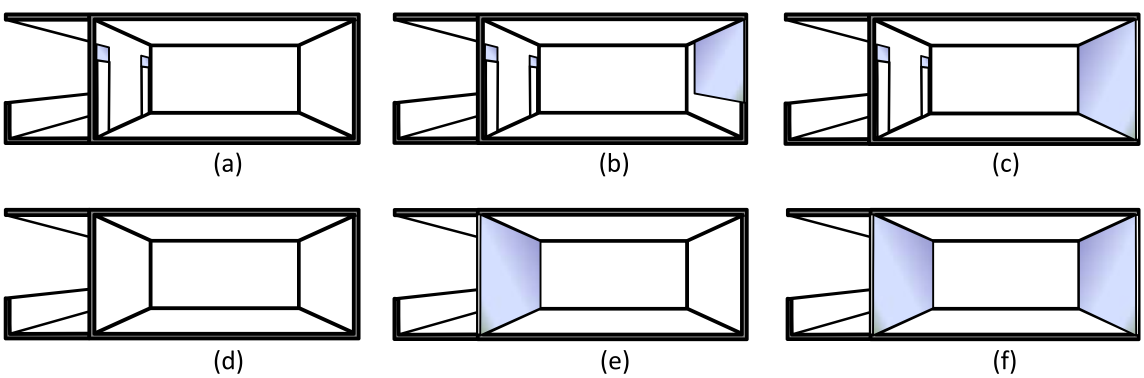


Fig.3. 4 Window area cases: (a) without window, (b) existing window, (c) fully glazed wall, (d) opaque walls, (e) fully glazed wall at the corridor side, and (f) two opposite fully glazed walls.

For comparative purpose, the sizes are transferred to be percentage mainly in WWR. The existing window contains 31.5% of WWR while it is 100% for the fully glazed cases. In opposite wall of the window, there are two small windows above the doors at the total WWR of 8%. The sizes were also estimated into WFR shown in Table 3.2. Six cases for each overhang depth were simulated while only existing window size was investigated in the physical study.

Tab.3. 2 Details of focused window areas.

Type	Main window			WWR of Opposite side window (%)
	amount	WWR (%)	WFR (%)	
Without window	0	0	0	8
Existing window (base case)	1	31.5	9.65	8
Fully glazed wall	1	100	32.69	8
Two opposite fully glazed walls	2	100	32.69	100
opaque walls	0	0	0	0
fully glazed wall at the corridor side	0	0	0	100

b. Shading devices

For shading devices, the focused parameters consist of projecting depth of shading device and internal shading. In order to focus projecting depth of shading device, simple feature of overhang, continually horizontal plane along the building, was assigned above the window wall. The optimised projecting depths of the device were calculated for each window area and orientation using shading optimisation function provided in Ecotect. The depths were transferred to be percentage of overhang depth to optimized depth in a specific window area and orientation. Example cases of southwest orientation were illustrated in Figure 3.5. There are 11 cases in total. It is no shading, existing overhang and optimised overhang cases for existing window (base case: BC) and fully glazed wall cases (FW). Optimised size of existing window area was also included in the fully glazed wall cases. The focused depths were concluded in Table 3.3.

Because the optimised depths of each orientation vary, percentage of optimised depth was used in order to compare avoiding differences of variables. While optimised depths suggested by Ecotect (example shown in Figure 3.6) were assigned to be 100%, other depths were proportionated to the optimised depth simply using the rule of three in arithmetic. The details are illustrated in Tab.3.3 with the values of metre depth and vertical shadow angle which are generally used for indicating shading size. For simulation technique, there are totally 32 cases of shading depth.

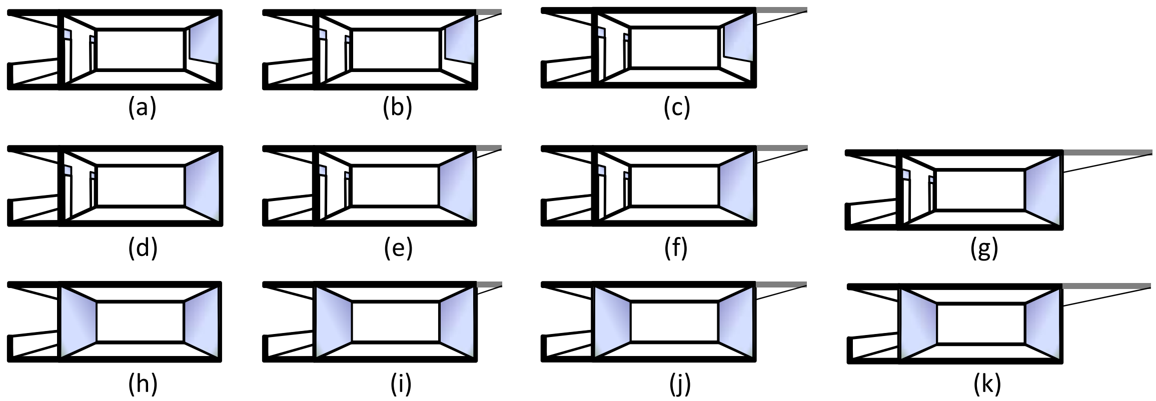


Fig.3. 5 Overhang depth cases for southwest orientation: (a) no shading for BC, (b) existing overhang for BC, (c) optimised overhang for BC, (d) no shading for fully glazed wall, (e) existing overhang for fully glazed wall, (f) optimised size of existing window area for fully glazed wall, (g) optimised overhang for fully glazed wall, (h) no shading for two opposite fully glazed walls, (i) existing overhang two opposite fully glazed walls, (j) optimised size of existing window area two opposite fully glazed walls, and (k) optimised overhang two opposite fully glazed walls,

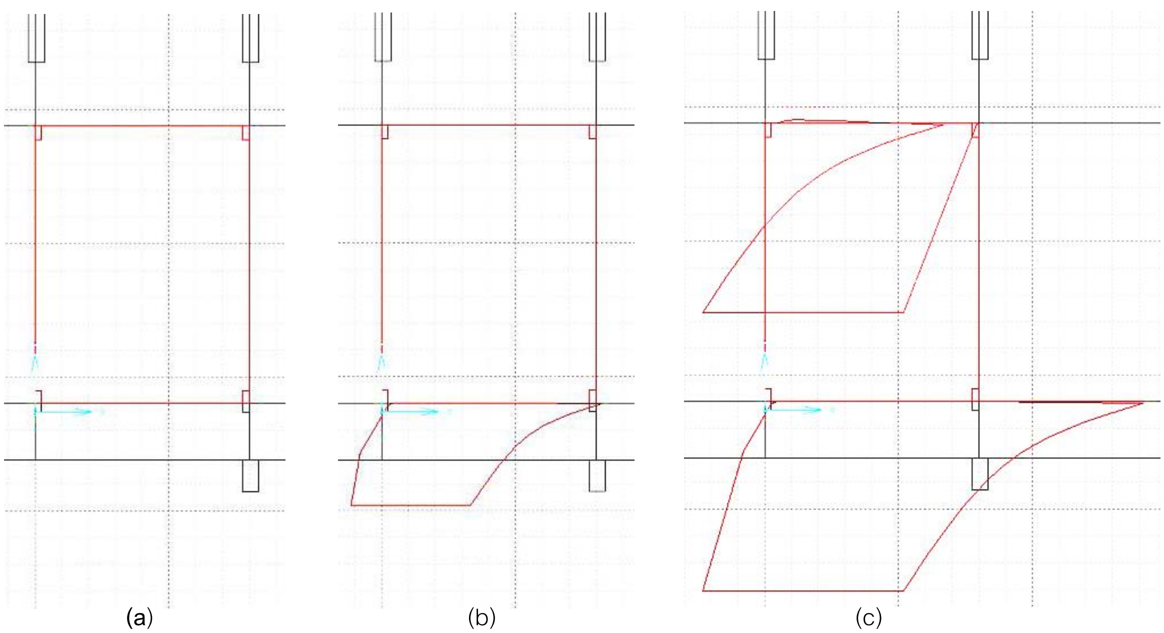


Fig.3. 6 Comparison of shading optimization by Ecotect for different window area: (a) existing window, (b) fully glazed wall and (c) two opposite walls fully glazed

Tab.3. 3 Details of focused overhang depth.

No.	Window orientation	Window area	Depth (metre)				Percentage of optimised depth (%)				Vertical shadow angle (º)			
			No shading	Existing case	BC optimisation	FW optimisation	No shading	Existing case	BC optimisation	FW optimisation	No shading	Existing case	BC optimisation	FW optimisation
1	N	BC	0	2.1	N/A	-	>100	>100	-	-	90	48.5	-	-
2		FW	0	2.1	N/A	N/A	>100	>100	-	-	90	58	-	-
3	SW	BC	0	2.1	6	-	0	35	100	-	90	48.5	23	-
4		FW	0	2.1	6	8	0	26,25	75	100	90	58	30	23
5	S	BC	0	2.1	3.5	-	0	60	100	-	90	48.5	34	-
6		FW	0	2.1	3.5	5	0	42	70	100	90	58	44	34
7	E	BC	0	2.1	3.5	-	0	60	100	-	90	48.5	34	-
8		FW	0	2.1	3.5	5	0	42	70	100	90	58	44	34
9	W	BC	0	2.1	5	-	0	42	100	-	90	48.5	26	-
10		FW	0	2.1	5	7	0	30	71.43	100	90	58	34	26

For internal shading, two types of them were focused. There is the existing device, which is curtain blind, and a recommendation type, which is a venetian blind. The impact of curtains was examined by physical measurement.

c. Window orientation

Previous studies generally suggested avoiding west window orientation while there are conflicts for practicality of south and north orientation. The main ideas of the suggestion probably are effect of direct sunlight on heat and glare control in west and south orientations and daylight availability in north orientation. The focus orientations therefore are the cardinal directions: north, south, west and east including the base case southwest. As the existing room orientation, southwest supposed to be the worst case because the sun normally paths in the south and located at lower altitude in the afternoon than in the morning. According to the sun chart diagram shown in Figure 2.6, the sun influences locations above the Equator mostly in the south. For tropical zones, which are located near the Equator, the sun also affects the north but only for a few months with high altitudes. In terms of sun geometry at different times of the day, the sun paths are symmetrical: sun angles of 8AM and 4PM are similar in the southeast and southwest for example. However, the working hour of the case study is from 9AM to 4PM. The altitudes of the sun in the afternoon during 3-4PM are generally much lower than that in the morning, which starts from 9AM. The orientation probably represents other ordinal directions. It is five orientation cases for prediction. The parameter was considered with influence of overhang depth focusing on influence of direct sun.

Only the southwest orientation can be assessed in the real building. Northwest may be another classroom orientation, but contexts of the room is different from base case particularly in terms of surroundings which have high impact on daylighting. The weather data of northwest classrooms was collected and compared to the base case to study impact of different orientation with cautions that they may not be commensurable directly.

3) Daylighting system

Because manual systems have been confirmed most practical for classrooms in general these group of parameters was investigated using survey and observation methods. Daylighting system in this study stands for the operating systems of façade and artificial light which occupants are responsible for. Contrast to automatic systems, not high efficiency of the devices but users' participation is the most significant factor for manual systems. Daylighting systems cannot work without users' willingness. For this parameter, problems of the existing systems were investigated by asking classroom occupants for their frequency and attitude of using natural light and observing their actual behaviour in their classrooms. Consequently, parameters in this context refer to façade operation method, lighting system, users' behaviour specific in operation of the systems and user attitudes to daylighting.

The parameters can be categorised for the use of method into three groups. Existing window area and overhang and impact of lighting system, internal shading which is curtain and window orientation can be examined using measurement and survey. For system operation, two main methods: survey and observation; were applied for investigating effectiveness of the systems, occupants' behaviour and attitude. In terms of design features, the parameters: window area, overhang depth and window orientation; were applied to simulation technique.

3.4 Indicators

For assessing practicality of existing façade and façade solutions, indicators are required. Indicators applied in this study mainly for daylighting quantity and quality. It is complicated to study both qualitative and quantitative aspects because indicators and methods are almost totally separated. It may be impossible to apply the same indicator to all aspect and make it simpler, but some connective indicators can be assigned to be analysis clues. A summary of all indicators is shown in Fig.3.4.

Illuminance is the major indicator for daylighting quantity that is available in every stage for measurement and simulation. The indicator then can be used for comparative analysis. Illuminance itself has weakness for indicating lighting distribution and availability of daylight. Frequently applications such as daylight factors and uniformity ratio were found impractical. Illuminance ratios were found that acceptable except the cases of insufficient lighting environment. For this reason, ratio of maximum and minimum was raised to apply with an indicator of sufficiency: percentage of the room that illuminance meet standard of 300-2,000 lux which has been adapted from some practical ideas of UDI. The minor indicator is *sunlight penetration* as it can be either benefit lighting quality or cause visual discomfort. The indicator can indicate efficiency of façade in terms of direct sunlight optimisation.

Tab.3. 4 Summary of indicators in different focus.

Category	Indicator	Focused scope				
		Lecture desk	Whiteboard	Projector screen	Overall environment	System operation
Daylighting quality	Users' behaviour vs. attitude	-	-	-	-	1 Sv
	Users' satisfaction	1 and 3 Sv	1 and 3 Sv	1 and 3 Sv	1 and 3 Sv	-
	Luminance	1 and 3 M	1 and 3 M	1 and 3 M	1 and 3 M	-
Daylighting quantity	Illuminance	1, 2 and 3 M and Si	-	-	-	-
	Sunlight penetration	1, 2 and 3 Sv, M and Si	-	-	-	-
Thermal aspect	Thermal comfort	-	-	-	2 Si	-
	Total cooling load	-	-	-	2 Si	-

Stage: 1=problem monitoring, 2=simulation stage and 3=application stage

Method: Sv=survey, M=measurement and Si=simulation

For quality, *users' satisfaction* was applied to be the main indicator while *luminance* of overall environment and the three tasks which are lecture desk, whiteboard and projector screen was combined in order to compare satisfaction rate with quantitative data. The vertical luminance at the eye level is the simplified metric which was used instead of visual comfort and glare indexes since the indexes was affirmed by previous research that cannot indicate real visual comfort sensation and moreover collection and assessment of glare is too complicated for the existing devices. Additional indicator for façade and system operation is occupants' behaviour versus their attitude in using daylight.

As an additional aspect, thermal prediction can indicate effectiveness of tropical façade design. In this study, the selected thermal indicators are thermal comfort and cooling load. For thermal comfort, *Fanger PMV* model was applied due to the fact that thermal environment of focused classrooms are generally controlled and the rooms were always applied air conditioning system for all occupied times. The indicator was applied for thermal condition without air conditioning system in order to study real interior weather. *Total cooling load* was applied to study energy used for achieving thermal comfort.

3.5 Surveys

Many techniques were applied for surveying the building and its users. The methods were used to intensively retain information regarding existing feature, application and problems of façade in terms of daylighting. The surveys can be divided into physical survey, classroom observation, occupants' satisfaction survey and survey for standard verification.

1) Physical survey

The physical survey is mainly for understanding building and façade nature in terms of dimension, elements and appearance. For accuracy of size study, construction drawing was included in the survey. Additionally, specification of materials and colours can be informed by the drawing. The study was focused from building site and surroundings, façade elements to room appearance including effect of daylighting source on the building and classrooms. Building and classroom photos were taken in order to collect physical characters that influence daylighting.

2) Classroom observation

The method was obtained during June 2012 when starting new semester. The focusing period was selected because the first and second week of semester is the time that the classroom fully occupied while the weather is normally too warm dissatisfied and less daylight. Lighting conditions of occupied classrooms was obtained randomly in all 60 seat classrooms. As lighting environment photos are comparable, simply photo taking is the main collection method of this stage.

For intensive study, the classes in AR205 and AR 206: where the weather data were simultaneously measured; were observed using an observation form (details can be seen in appendix A). The observation was obtained every 15 minutes from room preparation by lecturers until all occupants left the room. It concentrated in three aspects: use of visual tasks, operation of curtain and curtain, and the system operators including note for lighting environments of each condition. Other information such as modules, teacher name and numbers of students, were also collected because some specific characters such as teacher's personal habits, nature of modules, year of students. and density of the class may affect occupants' behaviour. It also can be used for further survey such as teacher interview.

There are 24 times of classroom observation in AR205 and AR206. The observation contains different types of modules and various teachers in both the morning and afternoon time slot.

3) Satisfaction survey

There are two satisfaction surveys were obtained in different times and purposes. The first survey was done at the first stage of research to study problems of existing façade involving daylighting. The last survey is for confirming occupants' satisfaction in a selected facade solution that cannot investigate by the simulation technique. The questions including scale applied in this study were modified from questionnaires of previous research in classroom or sustainability POE such as (Wong and Khoo, 2003), (Zagreus et al., 2004) and (Gupta and Chandiwala, 2010). The scale which was applied in the survey contains not only sensation in lighting environment but also comfort sensation scales.

a. Problem study

The surveys were obtained during June 2012 by questionnaire and interview. The surveys aim to investigate visual satisfaction of classroom users in general and to confirm users' opinions regarding the use and their attitude in using daylight. Other information such as personal profile or overall comfort was included in the survey because some of other factors such as vision problem or thermal satisfaction were assumed influence their answer. The last question of the survey is opened provided participants opportunity for mentioning other problems and suggestion for improving their classrooms in general in order to rate their comfort priority and avoid some absent topics that may relate to participants' answers.

Due to the number of participants, students were surveyed using questionnaire which asked in Thai language (the English version shown in Appendix A, questionnaire 02: satisfaction survey). For more intensive information, teachers who generally dominate classrooms were interviewed using questions in interview script (see Appendix A). The questions can be different from the script in case that the participant introduced some specific issues that had never been found in general. The participants included one of building architects who is a recent faculty lecturer.

The participants consisted of classroom occupants: lecturers and teachers; in all departments. There are 72% of all students (670 from 929) participated the questionnaire. The total size of all students excluded first year students who just started using the building for a few days before surveying, moreover, they normally used large auditorium without window. For the lecturers, all of them were expected to participate but, since the survey was obtained at one of the busiest periods of semester, only a limited number of teachers were available to be interviewed. In all, 39% of all teachers (16 from 41) participated in the survey.

b. Application

In the application stage, a satisfaction survey was obtained during December 2014, which is the winter solstice when the sky is most influenced by direct sun according to sun geometry. The purpose of the survey is to investigate occupants' visual satisfaction in a modified classroom. After façade solutions were concluded, most influential issues were raised for the survey. Participants which are lecturers and students were asked to rate their satisfaction of the modified classroom comparing to their regular classrooms. The method applied is questionnaire. For the students, they were asked to rate the satisfaction for the three visual tasks and lighting environments. They were allowed to sit autonomously while their sitting positions which probably influence their visual comfort were recorded in the questionnaire. Having different visual tasks, teachers were requested to rate their satisfaction in general. The questionnaires originated in Thai language the translated version is in appendix A, questionnaire 03-1: visual comfort survey (student) and questionnaire 03-2: visual comfort survey (lecturer).

The survey was obtained in the modified classroom at various time slots both in the morning and afternoon. The participants come from all departments. There are totaly303 students and 19 lecturers who participated in the survey.

4) Survey for standard verification

Standards in this case mean illuminance, illuminance ratios, luminance and luminance ratios. While the former stands for lighting quantity, this study attempts to use the rest for qualitative assessment. As there are some evidences confirmed that some of standards are either out of date or impractical, this stage was designed to verify practicality of selected recommendations for this research. The method applied to solve this issue is combination of satisfaction survey and measurement. 30 participants were asked to seat at 30 assigned positions for completing questionnaires while measuring illuminance and luminance at the same time. In the questionnaire (show in appendix A, questionnaire 01: visual comfort survey), the questions are about sensation and comfort of lighting environments for overall and the three tasks. The paper included measurement form that contains table for data collection.

The survey was obtained in AR205 while interior weather data for the unoccupied room of AR206 also was measured in order to calibrate the survey room to the base case. There are four daylighting conditions: opened curtain and switched on light, opened curtain and switched off light, closed curtain and switched on light and closed curtain and switched off light; that was repeated twice in the morning and afternoon. The participants were asked to leave the room while changing the condition in order to avoid influence of participants' expectation. The artificial light conditions: fully switched on case, fully switched off case and partly switched on cases; were investigated at night time when it was no influence of natural light. The results not only can verify the standards but also can provide impact of lighting system and curtain.

3.6 Measurement

Measurement was obtained for various purposes using very simple devices which are existent. Distribution of measured positions and the devices calibration are required for more accurate assessment.

1) Measurement cases

Determinate purposes consist of to collect weather data, assess lighting environment and support classroom observation. Measurement cases therefore can be classified by the purposes.

a. Collect weather data

Room weather data were obtained during June 2012 and December 2014 represent summer and winter solstice. The data were collected every minute in the middle of a sitting row from window to the opposite wall. It is one measure position outside and three positions inside the room. Two rooms were measured at the same time for three days. The collected data consists of temperature, RH, light intensity and CO_2 rate. The collection aim not only to study weather data in general but some of data also can be applied to verify prediction.

b. Assess lighting environment

Lighting environments were assessed in three cases. For studying the impact of existing façade is the first case the conditions were different orientation and combinations of lighting system and curtain use. The next assessment was compared to satisfaction survey for verifying visual standards. In application stage, light level of the modified classroom was assessed using the same method of the former cases.

The case of existing façade study and standard verification were obtained during June 2012 while it is December 2014 for the modified case. Data obtained consists of illuminance and luminance. Horizontal working plane illuminance was measured in 30 grid points at the time that four positions from external to internal were measured. The method including similar measurement in the base case classroom was applied avoiding impact of daylight fluctuation. For luminance, there are lecture desk luminance and nine positions of eye level vertical luminance. The measurements were repeated at least twice in different times in order to confirm the results.

c. Support classroom observation

The same method of weather data collection was also applied at the time of classroom observation. The purpose of this measurement is only for facilitate observation method because assessment by people is subjective and tend to be either overestimate or ignored. Extreme change of data can advantage analysis of occupants' behaviour in terms of daylighting system operation.

2) Devices

Existing devices are simple equipment that has been widely applied for assessing building environment in general. There are HOBO data loggers, Hagner lux meter, Minolta luminance meter and Telaire CO_2 meters. The photos of devices and specific visual tasks of each device were illustrated in Figure 3.7. HOBO data loggers are HOBO U12-012 Temp/RH/Light/External Data Logger. For temperature, the device measuring range is between -20º and 70º with accuracy at ±0.35ºc from 0º to 50º. The measurement range of RH is 5%-90%. RH accuracy typically is ±2.5% from 10% to 90%. The maximum can be ±3.5%. The device was designed for relative light level of indoor measurement at the typical range of about 11-32,300 lux while the maximum can be various between 16,000 to 48,400 lux. External input channel accuracy is ±2 mV ±2.5% of absolute reading. Hagner lux meter applied for this study is model E2-X. The measuring range of the device is between 0.01 and 199,900 lux with less than ±3% of accuracy and ±1 of last displayed digit. For Minolta luminance meter, the model is LS-100. Measuring range is between 0.001 and 200,900 cd/m^2 with accuracy of ±2%, ±2 of displayed value for the range of 0.001-0.999 cd/m^2 and ±1 of displayed value for 1.000 cd/m^2 and greater. Connecting to HOBO U12, Telaire CO_2 meters TEL-7001 can record 0 to 2500 ppm with accuracy at either 50 ppm or 5% of reading that is the greater. Data loggers and measuring devices were calibrated before the measurement programme started. The calibration details are provided below,

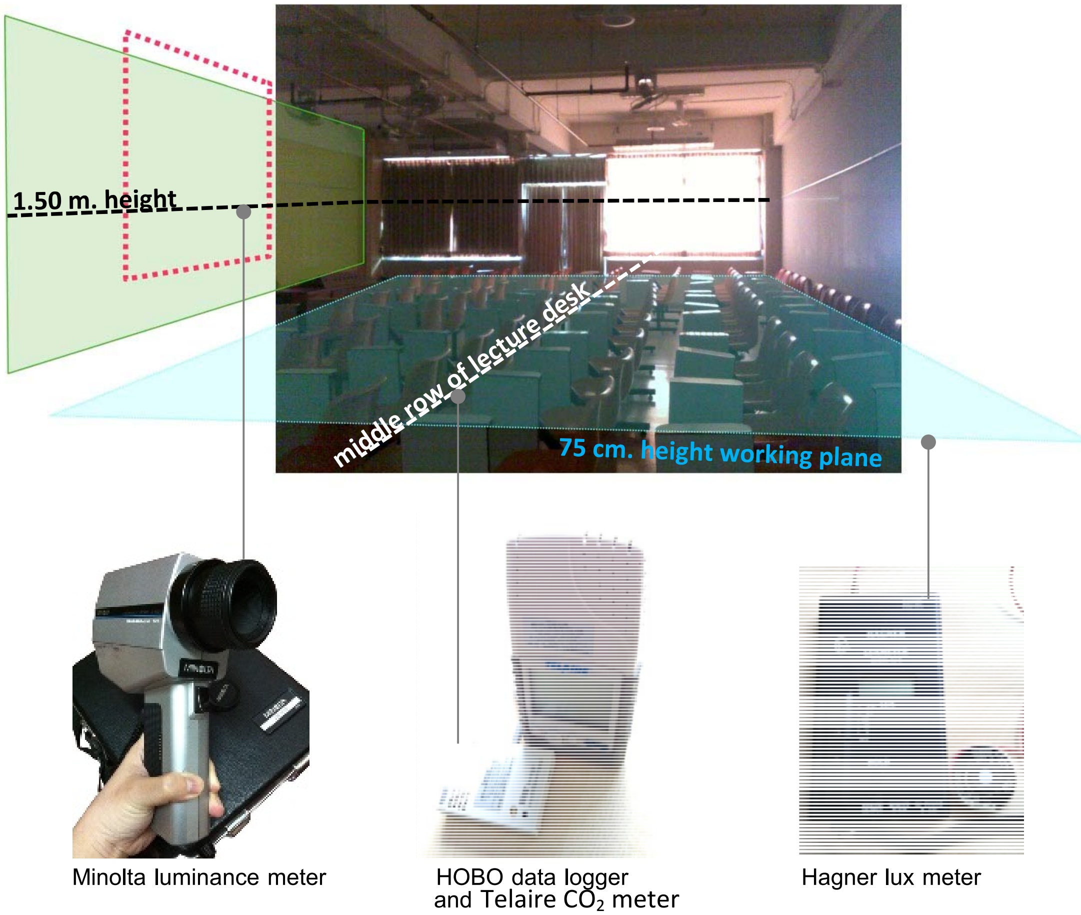


Fig.3. 7 Devices and their focused visual tasks

For measuring temperature, RH and illuminance, *HOBO data loggers* were applied in the line of middle row lecture desk which approximate to the centre line of room width. There are four devices for each room of AR206 which is the base case and other rooms. It is totally eight devices: HOBO number 3, 12, 2 and 11 from outside to opposite wall of window respectively for the base case and number 4, 1, 5 and 10 for other cases. The HOBO numbered 2 and 5, which were placed at the centre of the rooms, were connected with *Telaire CO_2 meters* for recording CO_2 data that measured by Telaire.

As a more accurate device, the Hagner lux meter was used to measure lighting distribution in 30 grid positions. Horizontal illuminance was measured at lecture desks which is 0.75 metre height. For luminance data, *Minolta luminance meter* was applied to assess luminance at 30 grid positions of lecture desks and nine point of eye level vertical luminance in each grid position. The vertical positions were distributed on the front wall and side walls at the height of 1.5 metres. Because the two devices can be measured one position in each time point while the daylight fluctuated, HOBO loggers were applied at the same time for calibrating differences of data.

3) Measured positions

Measured positions were assigned in context of the classrooms. There are three categories divided by use of indicators and devices. All groups of measured positions were concluded in Figure 3.8 for explaining the measurement overview.

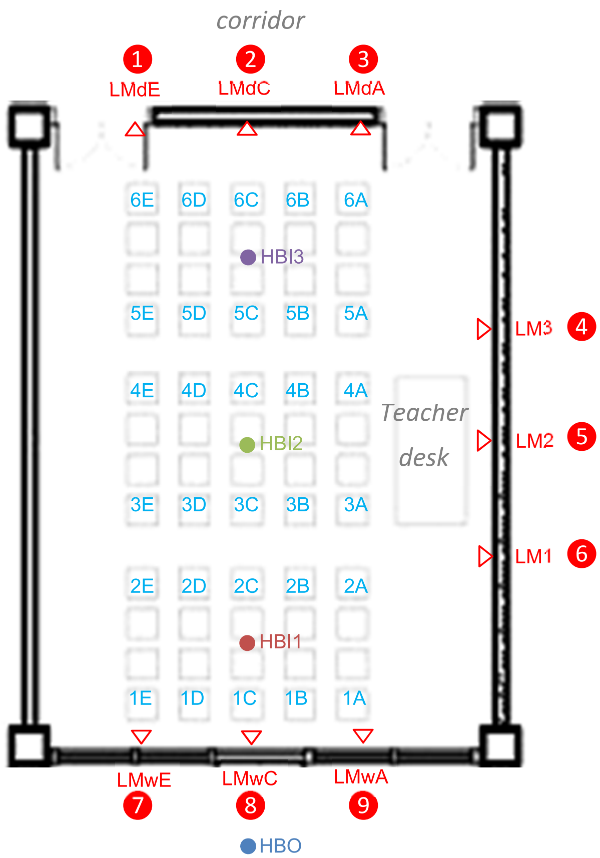


Fig.3. 8 Measured positions of the three devices.

Measured positions for the HOBO loggers shown in Figure 3.8 were at 0.75 metre height working plane in the middle row of lecture desks. While HBO stands for the device which was placed outside, HBI represents internal assessed devices: HBI1 the nearest position of the window, HBI3 the furthest and HBI2 at the centre of the room. The distance between the devices approximate to twice length of distance between devices and walls. Telaire CO_2 meter which was connected to the HBI2 was also placed at the centre of the room.

At the same working plane, 30 grid positions from five rows: A to E and six columns: 1-6 were measured for illuminance and luminance using a Hagner lux meter and Minolta luminance meter. The point of measurement is at the centre of the writing tablet.

From each of the 30 sitting positions, vertical luminance was measured from position 1-9 at 1.5 metre height. Positions from LM1 to LM3 are on the front wall: LM2 in the middle and on projector screen. LM1 and LM3 are about two metre far from LM2 in the window side and opposite wall side respectively. The positions are on the whiteboard area that adjacent to the projector screen. LMw and LMd positions stand for positions on the window side and corridor side respectively. LMwA and LMdA are in maximum visual field of right and left eyes (90º from line of sight according to (SLL, 2014)) of the participants who sit in row A. Based on the same criteria, LMwC and LMdC are for row C which is the centre line while LMwE and LMdE are for row E. Following the rule of general visual field of view, observers only in row E had nine points in their field of view. It is seven points for row D and C and five points for row B and A. there are 198 measured points in total for each case.

4) Calibrations

In order to avoid errors from different contexts of measurement like sensitivity of devices, fluctuation of natural light and unique of rooms, calibration methods were applied in this study. For the devices, correlations of data which was simultaneously collected by each device were formulated using regression analysis. Eight BOHO loggers were calibrated to HOBO number 11. The data from other loggers was calculated to be the data of HOBO number 11 to be comparable. For more accurate data, the data was calibrated to be equivalent to more sensitive devices. In this case, it is HOBO loggers with Hagner lux meter and Telaire CO_2 meters with Testo 535 CO_2 meter.

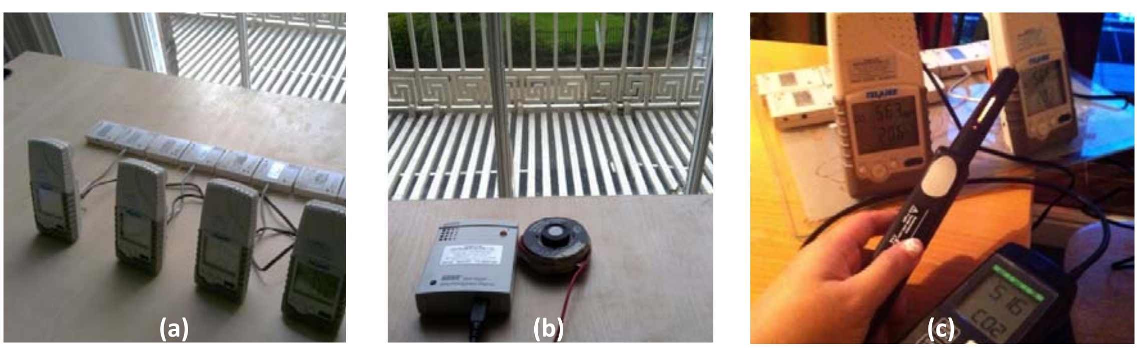


Fig.3. 9 Calibration of devices between: (a) the same types, (b) HOBO logger and Hagner lux meter and (c) Telaire CO_2 meters and Testo 535 CO_2 meter with extendable probe.

For calibrating the measurements of the Hagner lux meter at different times, a set of HOBO loggers were applied at the same time. Data from the devices were compared. Calibration will be considered only if there are significant changes of lighting environment. In order to calibrate the two adjacent rooms: AR205 and AR206; can be comparable, the weather data of same conditions was collected and analysed. Using correlation formula, the data of AR205 was calculated representing the base case which is AR206 before comparisons were made.

3.7 Simulation

After a review of available programs, RADIANCE was found to be a very important simulation tool for lighting studies, especially for its ability to access glare; Ecotect also was also frequently applied to many studies. However, RADIANCE was not used for this study because it has no function for thermal prediction, which is one of the most significant factors of façade design in hot climates. Ecotect may be able to deal with both daylighting and thermal aspect, but daylighting analysis is limited to diffuse sky conditions while the effect of direct sun generally dominates sky conditions in tropical climates. For these reasons, DesignBuilder was selected to be main software of this research, with its main advantages being that it is available for thermal simulation and daylighting analysis. Additionally, the program includes various type of sky conditions for which daylight levels at specific times and dates can be predicted. However, the function of daylighting analysis in DesignBuilder might be questioned as it is new and none of the previous research found by the author had used it for daylighting assessment.

DesignBuilder package version 3.4.0.041 was mainly applied while the daylighting analysis function, DesignBuilder new function, had been developed. In this section, data input and setting will be illustrated. Significant information of daylighting analysis which was studies at the mean time will be provided.

1) Weather data

Thailand weather data in the compatible format of the program: *.epw files; were investigated. In Bangkok (BKK) weather data are available in Climate Consultant IWEC. The predictions were compared to the BKK long-term weather data. Example of them was provided in Figure 3.10 for average outdoor temperature. The data were found similar to BKK long-term temperatures but different to winter data of Mahasarakham (MK), especially for December and January. The differences are probably because Mahasarakham and Bangkok are located at different latitudes and in different topographies. Mahasarakharm is at the centre of the large highland in the northeast which is directly influenced by winter monsoon from mainland China while Bangkok is located in a river flooding area next to the Gulf of Thailand, where there is an influence of winter winds from the northeast, is reduced by the mountain range of the high land in the northeast. Therefore, BKK weather data may not practical for applying to simulation model in Mahasarakham. When Meteonorm was applied, BKK weather data from the weather station are available but there is no weather station in MK. For this reason, weather data of the case study site was generated from Meteonorm using the coordinates of Mahasarakham University (MSU).

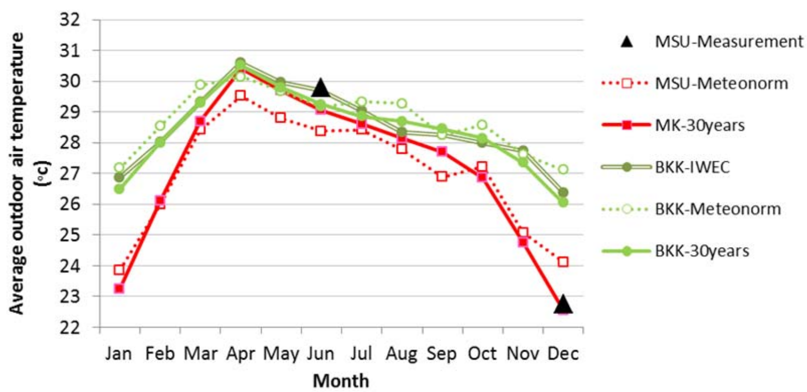


Fig.3. 10 Comparison of long-term, IWEC, Meteonorm and measurement average outdoor air temperature.

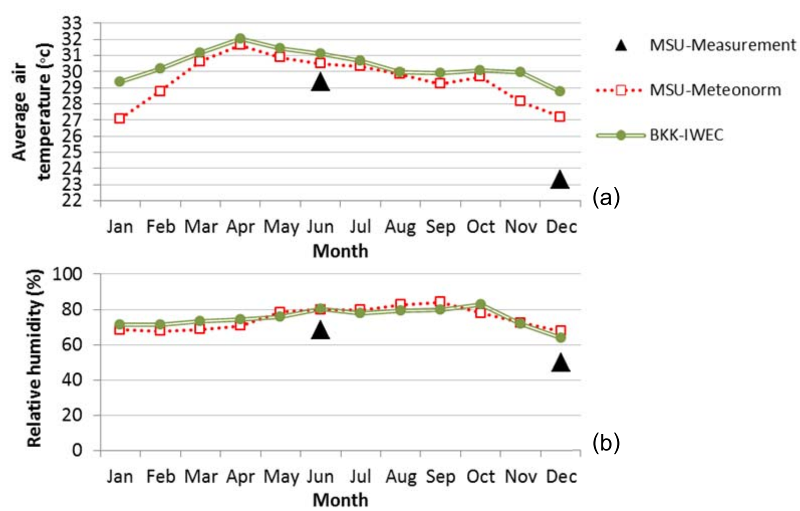


Fig.3. 11 Comparison of IWEC, Meteonorm and measurement indoor weather data: (a) average air temperature and (b) average relative humidity.

The generated data approximates to MK long-term weather data while it underestimates the physical measurements at the summer solstice and overestimate for that at the winter solstice. However, the differences are insignificant at not more than 2ºC. When considering interior data (Figure 3.11), data of MSU-

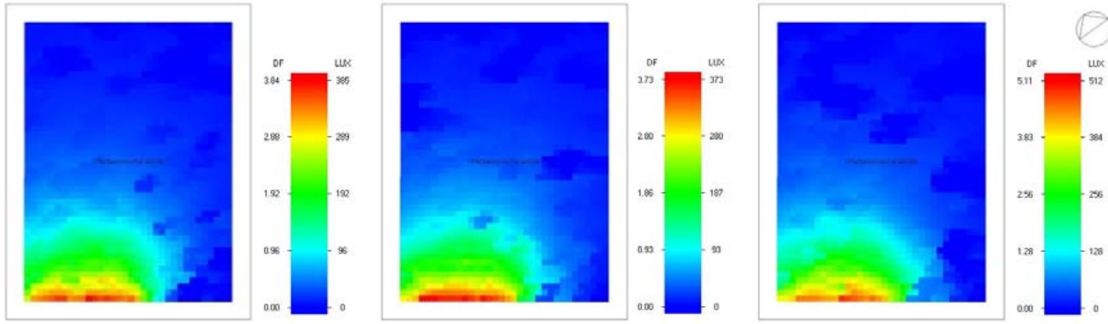
Meteronorm are insignificantly less than BKK-IWEC in terms of temperature, while there are similarities in RH. Measurement of RH and summer temperature also approximates to the generated data whereas the temperature is about 4ºC lower for winter. Consequently, the MSU-generated weather data from Meteonorm appears sensible for applying to the program with the note that it may provide slightly warmer data than real weather.

2) Model

The model of the case study was created using DesignBuilder. Although most of previous research generally applied to a specific space for daylighting analysis, the overall building with surroundings was also studied. According to the building lay-out (shown in Figure 3.3), there are few surroundings to affect the case study. They were already modelled in DesignBuilder (Figure 3.13). Apart from future work in other spaces is expected to study, significance of other building elements was found in the program study stage. In addition, many rooms were focused in this study. Their specific position and relationship between each other should not be ignored.

To avoid too much complexity, this study was specific in its analytical scope to room level rather than whole building level but, even then, when different scales of generated models were compared the predictions were different. For instance, the most realistic model (Figure 3.12(a)) provided higher illumination levels than the simplified model (Figure 3.12(b)). While the results are insignificantly different in terms of illumination level and distribution pattern, the simulation of the complicated model consumed much more time than the simplified one. Figure 3.13 illustrates a simplified version of the model which was generally used in this research. The model specified only lecture rooms as occupied spaces in building block (grey colour). Other building elements were assigned to be only component blocks (shown in pink).

Another influential factor is the choice of building materials. As show in Figure 3.12(c), when existing materials including actual reflectance were utilised, there was a significant change of prediction - more than 100 lux higher illuminance. It is probably because the room reflectance and glazing material of the case study provided more room illuminance than that of the program default. Consequently, the whole building model was applied using a simplified version which was set with real material information.



(a) (b) (c)

Fig.3. 12 Predictions of illumination level inside room AR206 under overcast sky condition for three models: (a) complicate model, (b) simplified model and (c) simplified model with as build materials

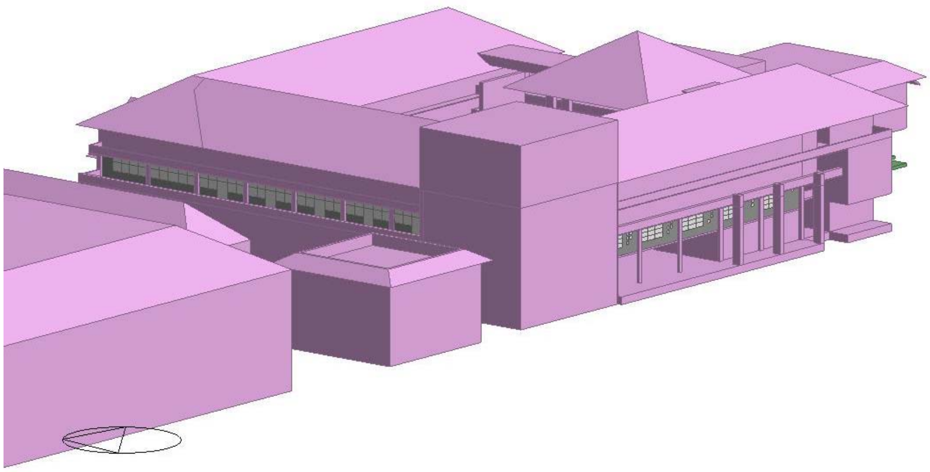


Fig.3. 13 Appearance of simplified model generated using DesignBuilder

3)Sky conditions

There are seven sky condition options provided in DesignBuilder: sunny clear sky, clear sky, sunny intermediate sky, intermediate sky, overcast sky, overcast (10,000 Lux) and uniform. Figure 3.14 and Figure 3.15 were generated from the same data but illustrate different approaches: Figure 3.14 shows illumination patterns in three positions of the room by section through window, while Figure 3.15 shows changes of illuminance during working hour in each position: HBI1 located near window (a), HBI2 is in the room centre (b) and HBI3 is at the furthest area from window (c). The predictions of most sky conditions contain similar graph shape of average illuminance through the room which contains the high illumination levels at the position near the window. The more it far from the window the more illuminance reduces (see Figure 3.14). According to the result, it can be divided into three groups. Firstly, sunny clear sky, clear sky and uniform are the conditions that have the highest average illuminance both in the morning and afternoon. The group of intermediate sky conditions has the different order in the two specific periods: the lowest in the morning and in the middle in the afternoon. It results in the overcast sky condition group also has the different order as the data are almost the same.

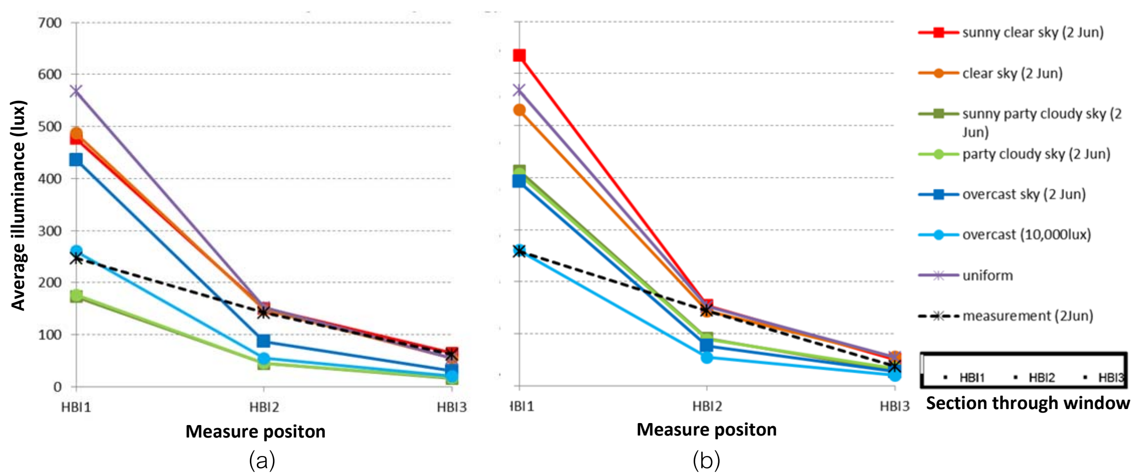


Fig.3. 14 Comparison of average illuminance predictions in seven sky conditions by room section: (a) in the morning and (b) in the afternoon

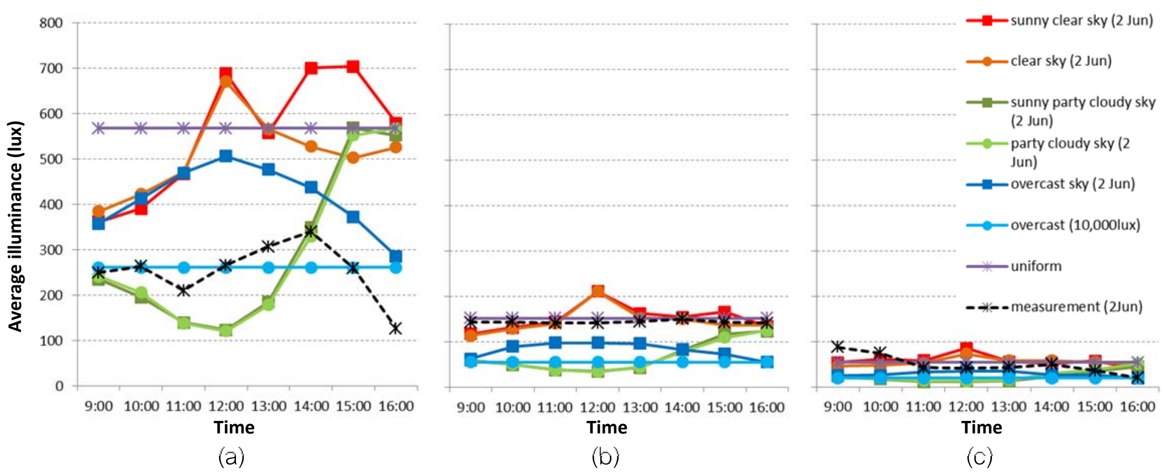


Fig.3. 15 Comparison of average illuminance predictions in seven sky conditions by time change at the position (a) HBI1, (b) HBI2 and (c) HBI3

There are two sky conditions that have set illuminance levels - overcast and uniform. The difference is the uniform illuminance is average in the highest group while it is in the lowest group for overcast. When the time was considered, illumination patterns of each sky conditions were different. At 12AM, while sunny clear sky, clear sky and overcast sky have the highest illumination levels it is the lowest for sunny intermediate sky and intermediate sky (Figure 3.15). The highest illuminance of the intermediate sky condition was rather at 3-4PM. Compared to the measurement, the highest group consisting of sunny clear sky, clear sky and uniform is the most similar in middle and window furthermost positions (Figure 3.15(b) and (c)) while it approximates to an overcast sky for the nearest position to the window (Figure 3.15(a)). In addition, the sunny clear sky condition has the most similar illumination pattern as its highest value included the 2-3PM, which is the highest illuminance of the measurement in general. For this reason, intermediate sky conditions appear impractical in terms of not only illumination levels but also time change patterns, although it has been confirmed to be the regular sky condition in the tropics. Considerably large range of various conditions in terms of amount of cloud in the sky is probably too difficult to be generalised. The variation of illuminance in different time tends to be an important parameter for tropical sky which is influence by direct sun. Instead of just selecting by its name, most similar pattern that the program can predict should substituted. While lack of previous sky report practicality of applying intermediate sky in simulation programs, the worst case of sky conditions was recommended (Steemers, 1994). For example, the prediction of lowest average illuminance can assess sufficiency of illumination levels. Consequently, the sunny clear sky and overcast were selected to represent the highest and the lowest illumination levels respectively.

4) Setting

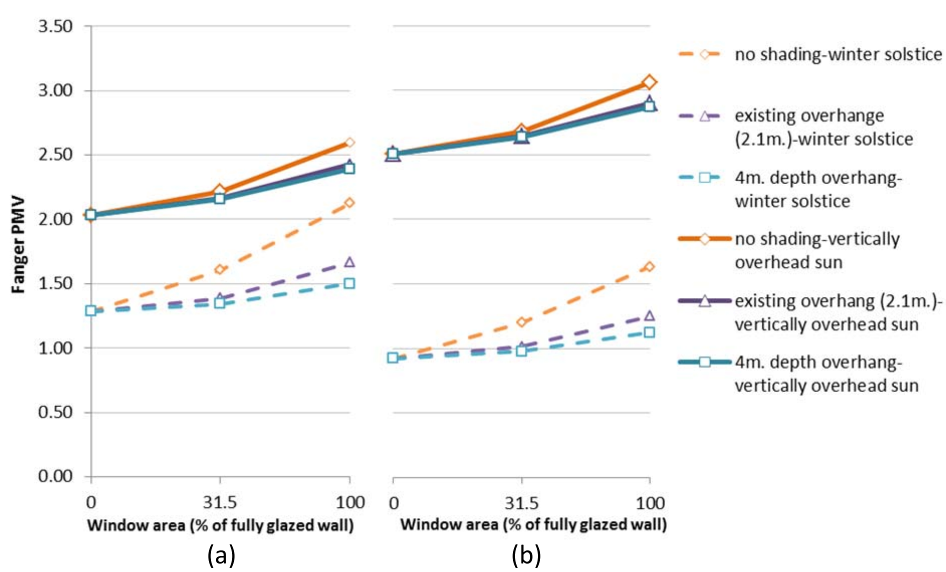


Fig.3. 16 Comparison of predictions in different weather data of: (a) MSU from Meteonorm with compact schedule, and (b) BKK from IWEC with 7/12 schedule

All alternative settings related to daylighting and thermal predictions were studied. Many comparative studies were analysed in order to understand program functions and select proper alternatives. Most default settlings were found sensible. Figure 3.16 is one example of the study that can indicate difference of operated schedules setting and weather data use. There are some changes due to unique of the case study. For activities and occupancy, the template of universities and colleges were applied with density of 1.5 people/m^2. According to suggestion from DesignBuilder programmer teams, operation schedule was set manually using working hour of the case study in compact schedule function. Specific materials and their reflectance of the existing building were added to the program.

For HVAC the cooling system was examined. The heating system was ignored as it has never been used in the country. Natural ventilation may be a comfort solution for the climate, but it is excluded because the focused space is generally controlled. According to previous research, while 22-28ºC was confirmed to be range of thermal comfort in controlled condition in hot humid climates (Mishra and Ramgopal, 2013), indoor recommended setpoint of air conditioning system for Thailand is 26ºC (Yamtraipat et al., 2005). However, AC setpoint temperature of the case study has been generally set at 25ºC or lower. The cooling set back of the program therefore is 28ºC but the setpoint temperature rather set in at 25ºC. The template of fan-coil unit and electricity from grid are fixed due to similarity to existing system.

For lighting system, target illuminance was set at 300 lux. A reference template was applied with a surface-mounted luminaire type. Unfortunately, the prediction of lighting energy consumption is available annually in average in building level but not for each room. Moreover, the pilot prediction showed the insignificance of lighting load although it is fully applied. Information of lighting energy then was excluded in this study,

Instead of lighting energy, the impact of artificial light on cooling load was investigated. The daylighting control function of the program was expected to be main method for confirming efficiency of daylighting solutions. In order to achieve daylighting control analysis, daylighting information is required. The models with lighting system and daylighting control, with lighting system without daylighting control and without lighting system were compared. Reasonably, significant differences were found between lighting and no lighting cases. Apart from lighting, artificial light can also increase heat load for cooling systems. With applied daylighting control, the cooling load was supposed to be higher than a no lighting case, but it unexpectedly approximated to no lighting case, which stands for daylight levels being always adequate, leading to no need for artificial lighting. The practicality of daylighting control was questioned because the illuminance prediction provided most insufficient values. After examining the cause of the issue, the function of daylight control was found using room average illuminance predicted from EnergyPlus that differ to prediction from daylighting analysis function based on RADIANCE. A comparison of results can be found in Figure 3.17. The two analysis functions work separately, as can be seen in Figure 3.17, and that the predicted grid of EnergyPlus is less frequent. The results are roughly predicted in 10 grid lines while daylighting analysis works at a pixel resolution of 46 grid lines. Comparisons of predicted positions are shown in Figure 3.17(b). Raw data from eplusmap in EnergyPlus, which was used for analysing daylighting control, appears to overestimate. All predictions meet the standard of 300 lux, although the sky in the predicted period provides minimum illuminance of the year. Daylighting analysis performs more sensibly. The illuminance rarely met the standard.

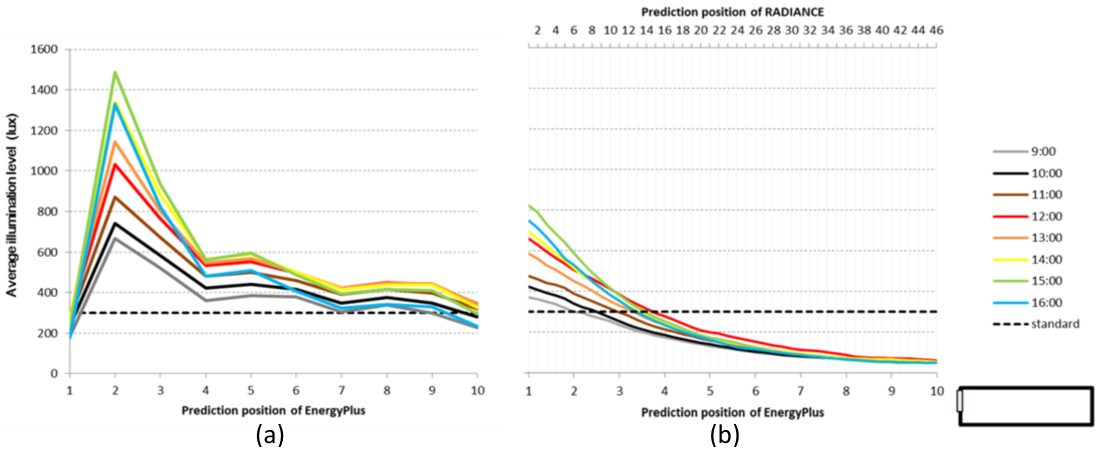


Fig.3. 17 Average illuminance prediction on 22nd of June in sunny clear sky using: (a) simulation function (EnergyPlus) and (b) daylighting analysis (RADIANCE)

The findings not only show the impractical of daylighting control for combining lighting and thermal analysis, but also reveal that simulation and daylighting analysis function of the program work separately. It implies that although only DesignBuilder can be applied for both daylighting and thermal analysis, the results remain unconnected i.e. the same as applying two independent programs. Analysis of thermal and daylighting in this research consequently was separate.

5) Verification

In order to confirm the practicality of the program, verification was required. Based on a validation process, three methods have been applied to previous research for assessing the accuracy of the simulation results. Galasiu and Atif (1998) compared measurement, calculation and results from other reliable simulation programs. Ramos and Ghisi (2010) and Sun et.al. (2016) compared predictions to real case study measurement. The measurement of scale models under artificial and real skies has been applied to validate the results in many pieces of previous research, such as Mardaljevic (1995), Aizelwood et al. (1998). While Mardaljevic (1995) found simulation can predict very accurate result comparing to measurement, many error sources were mentioned later by Mardaljevic (2004) as the main difficulty of these methods. Calculations using sky models such as the CIE standard clear sky model (Freewan et.al, 2008) and Perez sky model (Reinhart and Walkenhorst, 2001) also have been used for validations. Good agreements were found in most studies using artificial skies and sky models. However, Mardaljevic (2004) reported that the assumption of the CIE overcast sky conditions was unreliable for high fluctuations in illuminance. In a different approach, Ochoa et al. (2012) and Maamari and Fontoynont (2003) compared the prediction between different programs for validation. According to previous studies, the comparisons have been illustrated in different methods. Parametric regression models have been obtained in order to calibrate the results (e.g. Sun et.al., 2016). As a review of Tian et.al. (2001), four comparison methods have been widely used for program validation: using percentages of relative error, comparing illumination distributions along room depth, comparing illumination distributions in hours and comparing illumination distributions along linear line at 45°.

In this study, two validation methods were selected: daylighting analysis was compared to real building measurement and prediction with other programs. There results will be presented in regression model and illumination distribution in hours for comparison with measurement data. For comparing to other programs, illumination distributions along room depth and contour charts were selected.

a. Measurement data

The fluctuation of sky conditions during the measurements was found by Sun et.al. (2016) to mean that the measured data could not be exactly compared to the simulation program. Many large differences have been found between real sky conditions and sky conditions in simulation programs. Ubbelohde and Humann (1998) reported less difference between measurement and simulation under clear skies. Excluding effects of direct sunlight, the clear and intermediate sky was found to have more accurate results than the overcast sky (Galasiu and Atif, 1998; Galasiu and Atif, 2002; Fakra et.al., 2011 and Sun et.al., 2016). Good agreements were found, particularly in summer. However, differences of predictions from measurement can be large (Galasiu and Atif, 1998; Galasiu and Atif, 2002). They also found discrepancies by 50% for winter clear sky and overcast sky. Underestimation can be up to 60% for the cases under overcast sky. However, direct sun, which frequently has an impact on clear and intermediate skies, has been reported as one of the most important issue when comparing predictions to measurements. Direct sunlight, especially when entering into a space, results in considerably less accuracy or, in other words, large errors of simulation results (Reinhart and Walkenhorst, 2001; Gallasiu and Atif, 2002; Loutzenhiser et.al., 2007 and Sun et.al., 2016).

According to Galasiu and Atif (1998), the discrepancy between simulated illuminance and measured illuminance can be 100% in the conditions affected by direct sun.

The tropical hot-humid climate sky is generally very variable. It can change within a few hours from extremely high illuminance for a sunny clear sky with high angle sun to substantially lower illuminance under an overcast sky with thick cloud. Fakra et.al. (2011) found in their observation that global irradiance of intermediate day is approximate to that of clear day but with more fluctuation. Ng et.al. (2001) showed that a simulation program could provide precise internal illuminance predictions under overcast sky conditions, although errors were generally found because even in overcast sky condition the amount of cloud in a real Singapore sky was frequently fluctuating. Lam et.al. (1999), Wittkopf and Soon (2007) and Lim and Heng (2016) confirmed that sky models in most simulation program generally cannot represent all sky conditions in tropical climates. However, a reasonable one was selected for their study. They suggest that more refined sky representation might be required if accuracy is expected.

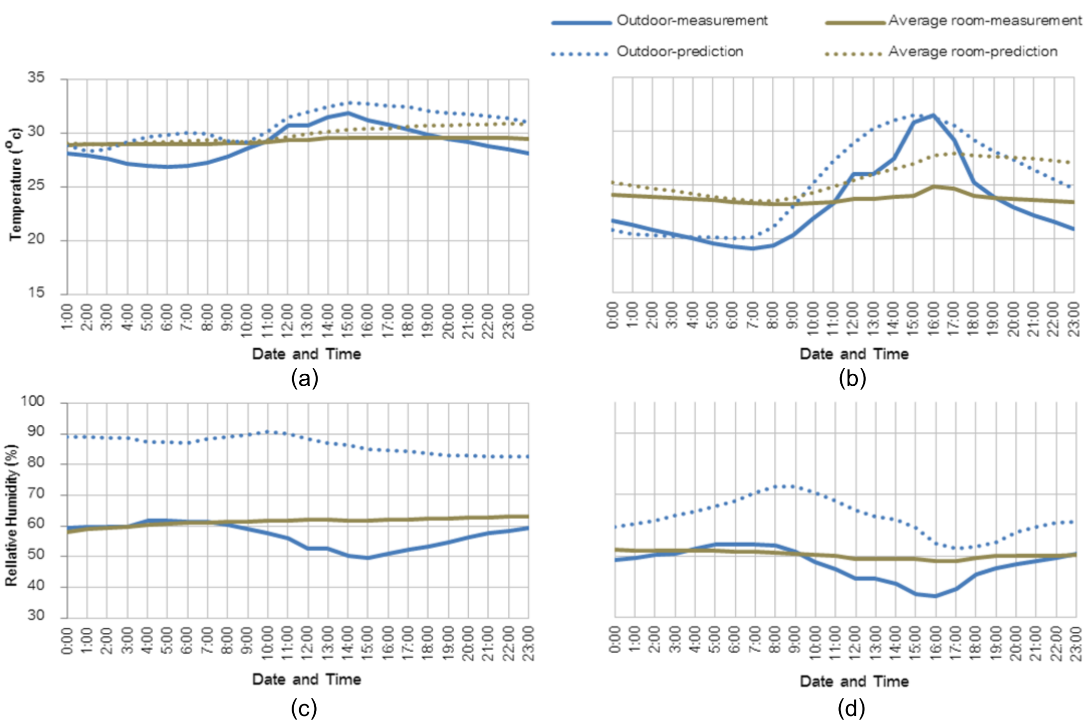


Fig.3. 18 Comparison of measurement and prediction weather data: (a) temperature on 19th June, (b) temperature on 22nd December, (c) RH on 19th June and (d) RH on 22nd December

As it has been mentioned, weather data applied in this study appear acceptable when compared to measurements. The data which were focused on were temperature and RH due to them being important thermal comfort factors. Figure 3.18 and 3.19 provide more details in terms of temperature and RH, and illuminance respectively. For temperature (Figure 3.18(a) and (b)), predictions little overestimate for outdoor and indoor data both in winter and summer. The data in summer appears less different to the measurement than in winter. Hourly patterns are also similar which is steady for room temperature and peak at about 3-4PM for outdoor temperature. For RH, the pattern appears similar while higher the measurement especially in summer. The maximum difference is approximately 35%.

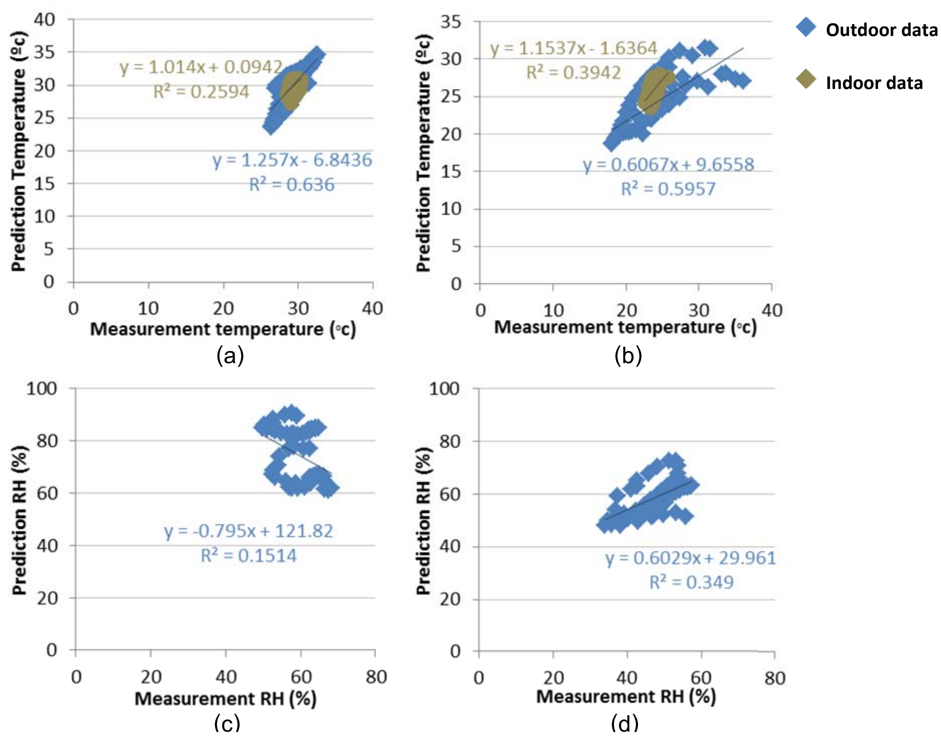


Fig.3. 19 Relationship between measurement and prediction weather data: (a) temperature during June, (b) temperature during December, (c) RH during June and (d) RH during December

When sunny clear and overcast sky conditions were applied, the prediction was acceptable in terms of illuminance level and pattern only if the results of both sky conditions were integrated. Figure 3.20 illustrates the comparison details in this case. The sky condition during measurements was partly cloudy sky with some influence from direct sun, which is the common sky type in Thailand. The amount of cloud in this sky type can vary from 30% to 70% of cloud-cover area over the sky hemisphere. Therefore, the measured illuminance was expected to lie between the illuminance under a sunny clear sky and an overcast sky. When the level was ignored, the lighting changes by time change were similar. The illuminance in summer reached the peak during the afternoon then reduced at around 4PM, while the peak in winter was at 4PM. Daylight measurement results were like predictions of sunny clear sky on average, expect in position HBI1 and during 3-4PM in winter when the predictions were significantly overestimated. The results reveal the practicality of data from the type of sky in the areas with less influence of daylighting sources. It is noted that the predictions near the window area were much more than actual levels, therefore, the actual variation will be not much as prediction. Figure 3.21 shows that the predictions are approximately three and ten times of the measurement for summer and winter respectively. The proportions probably refer to data at HBI1 position and 3-4PM in winter due to the fact that there is no significant difference for the rest data. The predictions of overcast sky generally can be used as minimum level. Moreover, due to their similar value, the overcast sky data can represent the value of HBI1 in average.

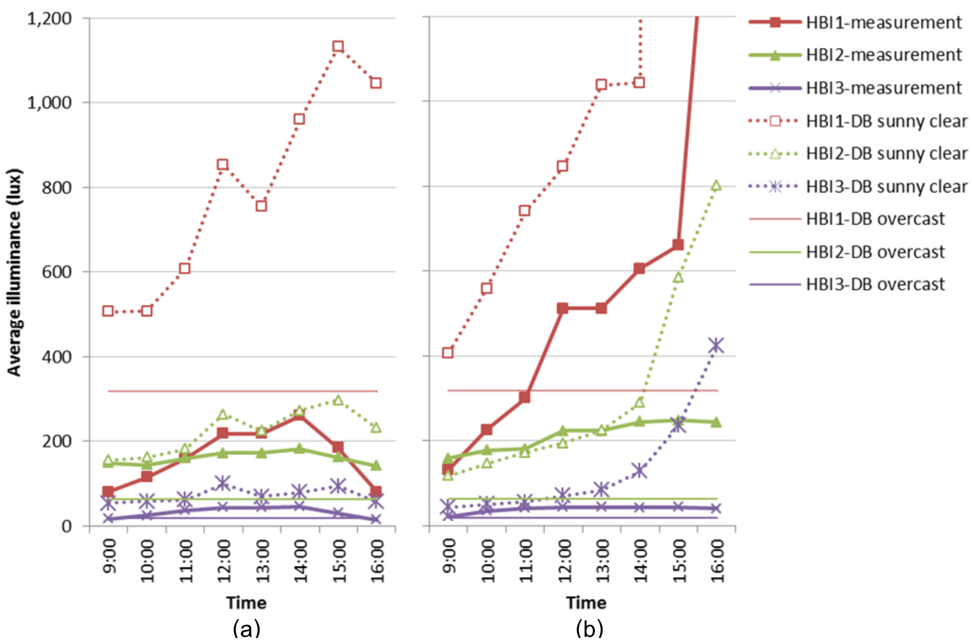


Fig.3. 20 Comparison of measurement and prediction average illuminance: (a) on 22nd June and (b) on 22nd December.

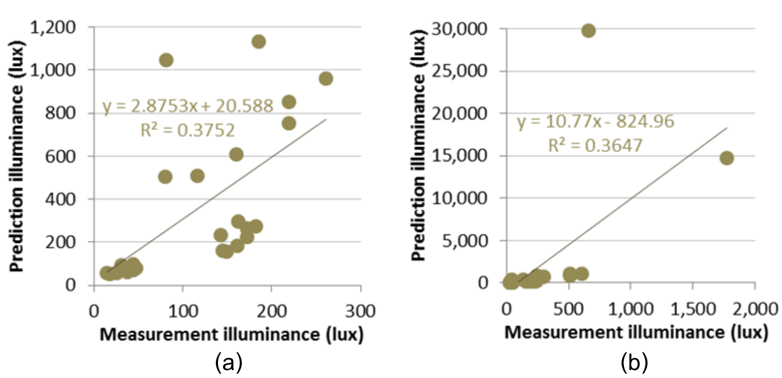


Fig.3. 21 Relationship between measurement and prediction of average illuminance: (a) on 22nd June and (b) on 22nd December.

Agreements between the results of simulation and measurements have been found in many pieces of previous research. Many studies test the validation of simulation programs by plotting predicted against measured values, with the size of the coefficient of determination (R-Squared or R^2) indicating the strength of the comparison. A R^2 of 1 shows a perfect agreement between the measured and predicted value. A low R-Squared value might be important for demonstrating that predictions can be different to observed data. A low R^2 can be acceptable, especially in studies where the variables are complex and frequently changing during a measurement period, while those fluctuations cannot be easily modelled in a simulation program. variables. In this study, relationship between measurements and simulation were examined in order to provide information and it was found that the range of differences could be about three to ten times overestimated when comparing to the measurement. A low correlation of illuminances between measurement and simulation can occur in the situations that there are fluctuations of real skies. A study in a tropical climate by Ramos and Ghisi (2010), for example, found a R^2 of 0.48 in the case of an overcast sky. Different types of intermediate sky also had low R^2 values, from 0.41 to 0.58. The correlations found from this study are shown in Fig.3.19 for temperature and humidity and in Fig. 3.21 for illuminance. The range of R^2 values range from 0.15 to 0.64. Although the R^2 values are generally not high, they are considered to be acceptable in the context of thermal and lighting measurements made under tropical conditions. The values are similar to some of the studies previously quoted. All evidence confirmed that the prediction of DesignBuilder can, in general, indicate lighting and thermal environment sensibly. The program appears most accurate for investigate the sufficiency of illuminance while it may overestimate thermal conditions For high levels of illuminance, which were influenced by daylighting sources, the program also overestimates and probably leads to excessive variation of illuminance.

b. Illuminance prediction of Ecotect

An alternative software, Ecotect, was also considered. Predictions of illuminance were focused on in order to check reliability of DesignBuilder predictions. The selected sky condition was overcast sky (10,000 lux) as it is the only condition provided in Ecotect and can be compared to the overcast sky conditions of DesignBuilder. The programs work at different pixel resolutions, 37x49 for Ecotect and 34x46 for DesignBuilder. Grid lines were compared in Figure 3.22(a). The result in Figure 3.22 shows that the contour patterns of the graphs are similar, but the illumination levels are different. As shown in Figure 3.23, predicted illuminance from Ecotect is approximately 150 lux higher than DesignBuilder predictions. When consider measurement data in Figure 3.20, the predictions of Ecotect may be more similar for positions HBI1 and HBI2 but it overestimates values for the darkest position: HBI3.

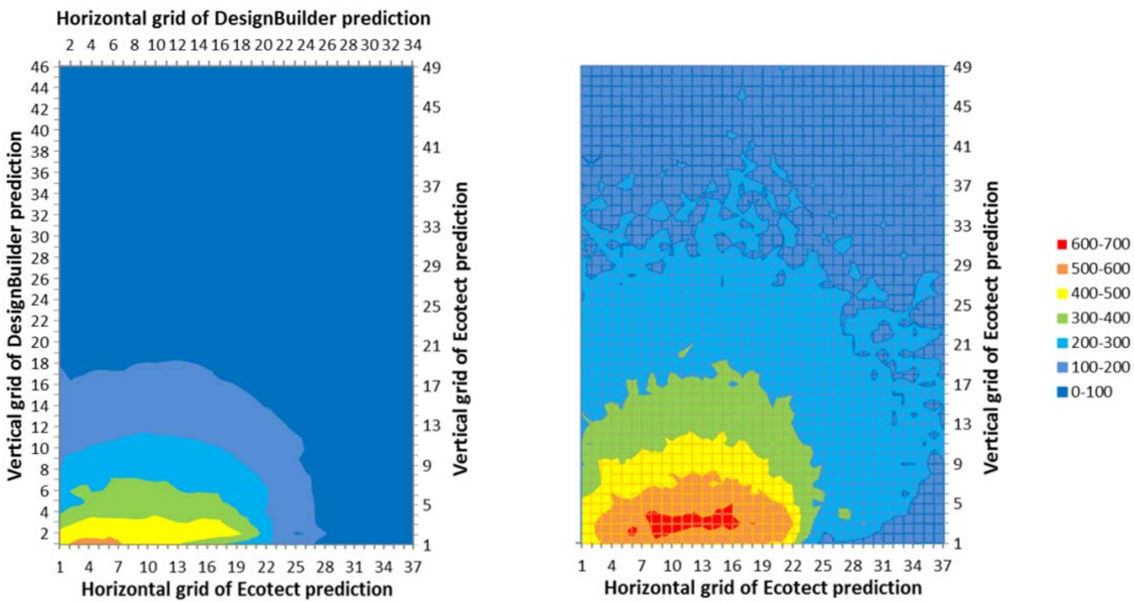


Fig.3. 22 Comparison of the daylighting predictions produced by: (a) DesignBuilder and (b) Ecotect.

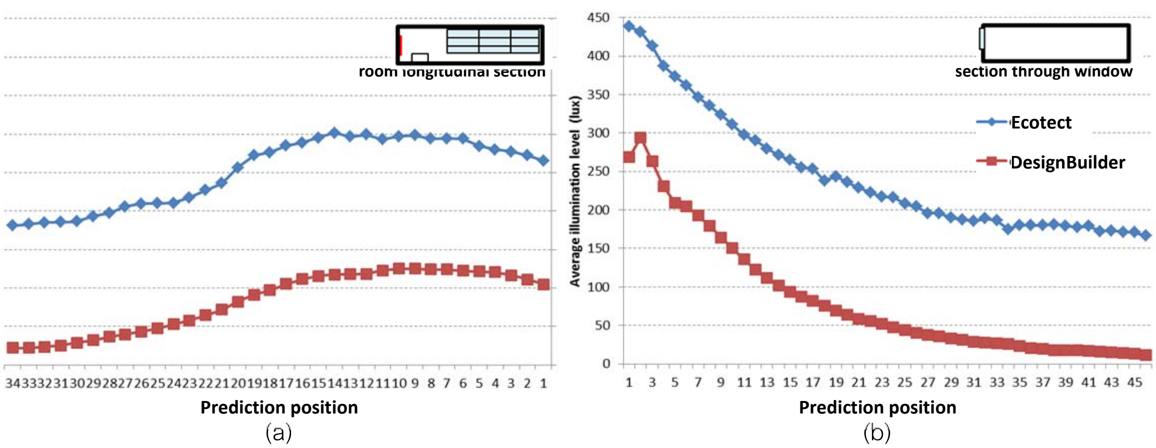


Fig.3. 23 Comparison of the average illuminations predicted by DesignBuilder and Ecotect by: (a) room longitudinal section and (b) section through window

It possibly confirms the accuracy of the prediction in DesignBuilder because it can indicate not only influence of direct sun but also sufficiency of daylight level. However, the program contains some significant limitations that must be considered at the various stages of analysis.

c. Application of base case

Apart from errors created by different sky types and the fluctuations of real sky conditions, comparing daylight measurements to predictions may also involve other sources of error. For example, according to a review of previous studies, it can be concluded that discrepancies between simulation and measurement can found in the point of measurement/modelling in a room. Predictions for positions close to a window were found to have the lowest accuracy, with errors greater than 50% being found (Mardaljevic, 2001; Reinhart and Walkenhorst, 2001; Tian et.al., 2001 and Yu, et.al., 2014). Lam et.al. (1999), Tian et.al. (2001) and Fakra et.al. (2011) affirm that not only near window positions but also far away positions are hard to predict precisely. Li and Lam (2004) confirmed that result by showing errors as high as 67%. The discrepancies result from limitation of the programs in calculation and modelling. For positions close to the window, higher error rates occur in cases which were affected by low angle sun (Ubbelohde and Humann, 1998 and Sun et.al., 2016). This reveals the impact of direct sunlight. Even the most accurate simulation program has been found that have limitations in calculating transmission through window and external obstructions. Although it is known that RADIANCE can precisely simulated models with translucent material, applications of clear glass still had errors. Reinhart and Andersen (2006) claim that it is due to impact of direct sunlight. Limited capacity in modelling outdoor environment, surroundings and external obstructions of simulation program can also be another cause of this difficulties (Ng et.al., 2001). Multi-reflections among interior surfaces and reflecting façade are the main difficulty for the far positions from window. Many lighting simulation programs only simply calculate the reflections which cannot exactly represent the reality.

Secondly, errors frequently result from the fact that simulation models cannot generate simulation to be exactly the same as reality. A limitation of RELUX, for example, is that it does not provide sufficient options for thickness of façade and outdoor reflectance setting (Yu, et.al, 2014). Mardaljevic (2001) points out that just one-millimetre difference between a model and a real buildings can produce great discrepancies in results. Lastly, when various design alternatives were examined, simulation software might calculate each case with different ranges of errors (Maamari et.al., 2006). For instance, most of software package have difficulties in predicting indoor illuminance in rooms with reflective façades and provide higher error rates than that in simple window cases.

In order to deal with these difficulties, a reduction of the discrepancy as much as possible is the ideal solution but it is time consuming and requires expertise. Less accurate models can be unacceptable for some situations. Sarawgi (2004) affirmed that, although errors were found, prediction is sufficient for making design decisions when comparison of design alternatives is more practical than proving a hypothetical final solution. A specialist engineer, P J Greenup, also suggests that comparative studies have been generally applied for examining differences between several design options Mardaljevic (2004). Greenup further states that more precision is not needed for this case. For solving error problems, Maamari et.al. (2006) present their results by means of upper and lower tolerance bounds. Saraiji et.al. (2015) proposed a daylight metric called *Normalized Daylight Performance Index* (NDI) which is the ratio of relationship between illuminance of a base case and each design alternative. The ratio not only indicates changes when improving the design, but it can also give good agreement between simulation and measurement. Most design alternative studies emphasis their improved designs by comparing to the base case. Lim et.al. (2013), in a study in a tropical climate, investigated the daylighting performances of internal shading designs focused on their potential range compared to a base case. Studies in separate design alternatives include: Lim and Heng (2016) for dynamic internal light shelf, Lee et.al. (2016) for shading design, Moazzeni and Ghiabaklou (2016) for light shelves and Lee et.al. (2017) for perforated light shelves; also applied base cases for investigating design efficiency.

In this study, a base case was also selected to assess differences between design alternatives in order to reduce errors which could occur between different alternatives resulting from limitations of the simulation programs. For solving difficulties of sky fluctuation, the results were obtained using predictions under sunny clear sky as the maximum and overcast sky as the minimum range.

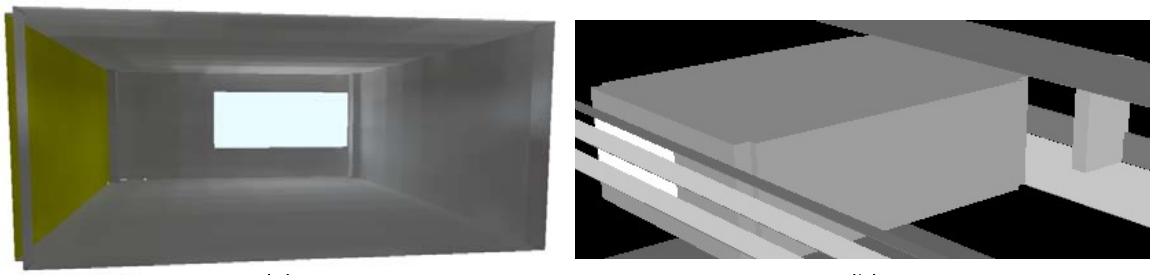
6) Additional analysis

Other related parameters include reflecting light strategies and the use of natural ventilation. Although it is not included in thermal parameters, a reflecting strategy is one of the most important solutions for sidelighting design. The performance of reflecting devices should be investigated for further daylighting improvement.

Façade design for daylighting appears to create a risk to obstructing natural ventilation. Analysis of ventilation was added to this study in order to study the possibility for applying natural ventilation of the suggested facade. The studies were analysed separately due to other type of simulation and specific devices are required.

a. Reflection analysis

According to a literature review, reflection of lighting, especially for natural light, is one of difficulties of all lighting simulation software. Daylighting analysis function in DesignBuilder was found to be not compatible for analysing reflection from outdoor elements. Another daylighting simulation software is required for this specific analysis. DIALux 4.13 was selected for this purpose. As the base case, room AR206 was modelled using existing the façade, room and ground reflectance (the model is shown in Figure 3. 24).



(a) (b)

Fig.3. 24 DIALux simulation model (a) base case model after daylighting analysis at 9:00AM of 22nd Jun. and (b) outdoor model of base case with shading device, top and window bottom light shelves.

Difference types of façade were applied to the model: three window types, three shading depths and various types of light shelves. Selected from the previous simulation, the existing window, fully glazed wall and two opposite fully glazed walls with no shading, existing overhang and four metre depth overhang were re-analysed. Types of light shelf combination suggested from previous research were simulated and compared to the window and shading cases. In order to conclude impact of reflecting strategy, significant improvements were selected and reported. The models were simulated hourly in working hour under overcast sky and sunny clear sky on 22nd June and 22nd December.

In order to study differences from DesignBuilder, the results in the same condition were intensively compared. Results shown in Figure 3. 25 illustrate the different results of the two software. Results from DIALux were found averagely 100-200 lux higher than DesignBuilder results. The differences can be higher in the area next to window. In contrast, DesignBuilder appears to overestimate the effect of direct sun (Figure 3. 25 (c) and (d)). Comparing to measurement (shown in Figure 3.14, 3.15 and 3.20), results from DesignBuilder were found to overestimate near the window area, especially when the room was influenced by direct sun. In the rear areas of the room, the DesignBuilder results were similar to the measurement. DIALux appears to overestimate daylight illuminance in general. Although DIALux generally overestimated illuminance, the patterns of predicted distributions were sensible compared to results from DesignBuilder and the measurements. Moreover, the software appears to be responsive to additional reflecting elements. For those reasons, the results were used for studying differences between reflecting cases.

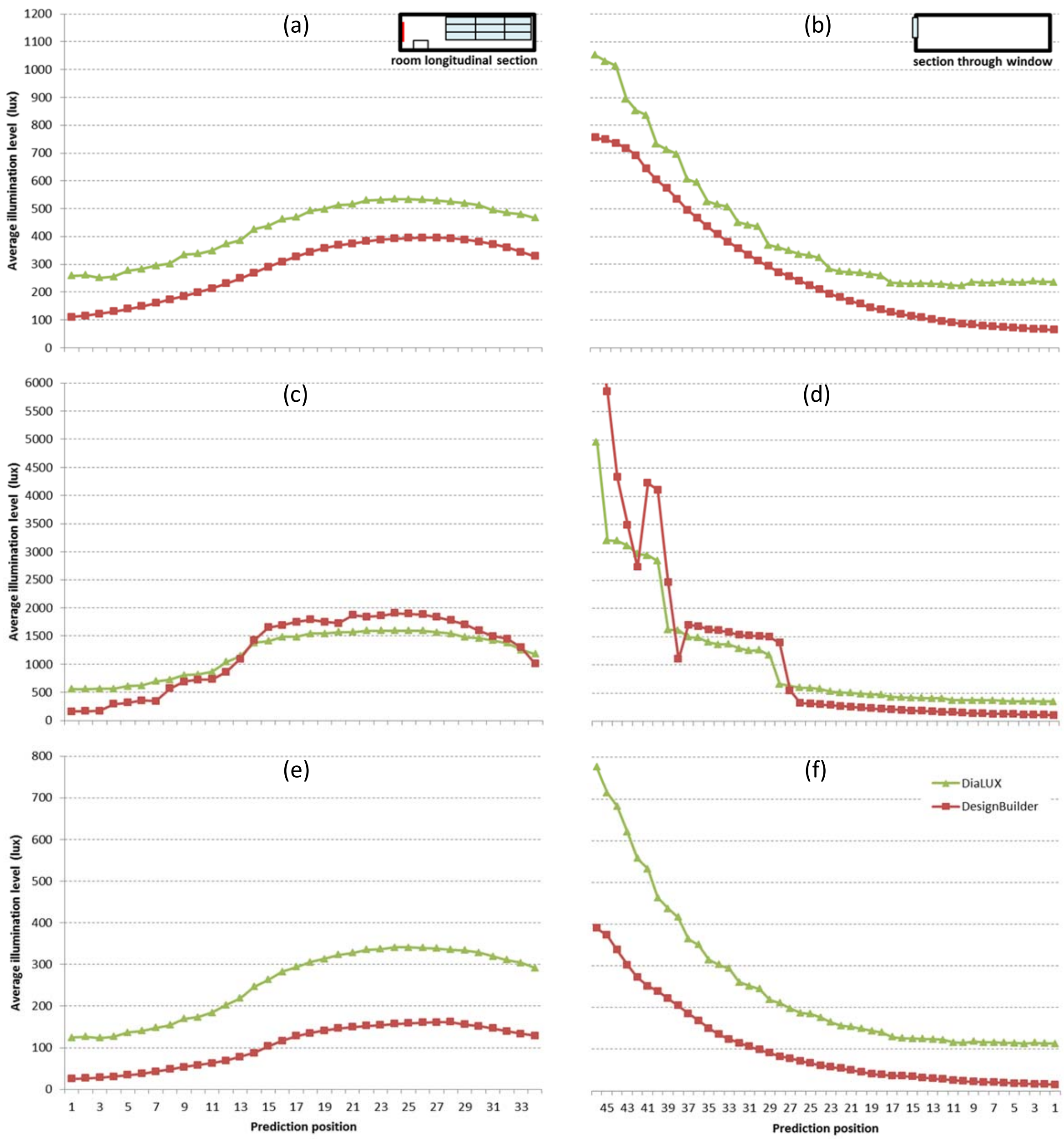


Fig.3. 25 Comparison of the average illuminations predicted by DiaLUX and DesignBuilder under (a)-(b) sunny clear sky on 22nd of Jun. (c)-(d) sunny clear sky on 22nd of Dec. and (e)-(f) overcast sky

b. Air flow calculation

Analysis of natural ventilation, which has been used in most simulation software, is complicated and works separately with other parameter calculations. As it is an additional analysis, the simple function like air flow rate calculation was applied for examining the natural ventilation performance of the suggested classroom façade. Using the EnergyPlus function built in DesignBuilder software version 5, the air flow rate simulation was used to analyse the same models as were used in the thermal and daylighting analyses. The models were set in the same condition as previous, except the setting of AC and window operation. The AC was turned off while the windows were fully opened. The selected cases were simulated with hourly natural ventilation rates during working hour in the same five specific months as the previous simulation i.e. March, April, June, September and December. Average air flow rates were compared in order to study differences of ventilation rate in different façade features and months.

3.8 Method of generalisation

For generalising the findings of this study, additional case studies were included in two stages: problem study and application stage. It was attempted to follow the method of the main case study in order to make data comparable.

1) Criteria of additional case study selection

Focusing on 50-60 seat university classrooms in four regions of Thailand which use AC and the same type of teaching devices, a brief survey using documents and information provided by university staff were obtained at the beginning of the additional case studies process. Apart from classroom location and basic feature, support from building owners would be one of the key criteria. In order to compare their results, the surveys should have done in a short term. Facilitations for informing participants and circulating the questionnaire were required, especially for repeating the survey in case of errors. Classrooms in six buildings could be surveyed: one in the northeast of Thailand, two in the central area, two in the north and one in the south region. Data were collected during the March equinox when general classroom conditions, occupied and unoccupied, are available to be surveyed. However, there were errors occurring during the surveys, resulting in delay and incomplete data sets. Finally, four classrooms were selected as additional case studies. There were the room SNP3 in SNP Building of Faculty of Architecture, Khon Kaen University, Khon Kaen in the northeast region; room 1712 in Building number 19 of Faculty of Science, Srinakarinwirot University, Bangkok in the central region; room 5111 in the Maths building, Faculty of Science and Technology, Chiang Rai Rajabhut University, Chiang Rai in the north region and the room 5406A in Building number 5: Academic service center, Prince of Songkla University Phuket campus, Phuket in the south region.

2) Problem study

In order to generalise the daylighting problems in 50-60 seat university classrooms, the same method used in the main case study were applied to each case study.

a. Survey

Each survey consisted of classroom physical survey and occupants' satisfaction survey. Because most of the case studies didn't have the building construction drawings, room measurement and drawing were included in the physical survey. Data collected in this survey are shown as architectural drawings in Appendix B. The surveys consisted of lecturer interviews, student questionnaires and class observations using the same devices given in appendix A i.e. Interview script, Questionnaire 02 and Observation form respectively. The surveys were obtained during March 2017 with an expected number of at least 150 questionnaires. The usable questionnaires were concluded at the numbers of 158 for Arch KKU, 150 for Sc SWU, 171 for Sc CRRU and 250 for PSU.

b. Measurement

The additional case studies were measured using the same devices as in the previous measurements, but the measured positions were reduced to be two points: the outdoor position (HBO) and at the room centre (HBI2). The positions were also the same positions as the previous measurement shown in Fig.3.8. Occupied and unoccupied conditions were expected for the measurements; therefore, the measured periods were set following the class schedules. Temperature, RH, illuminance and CO_2 were collected separately for each case study: 8th-9th March 2016 for 5111 of Sc CRRU; 16th-17th March 2016 for 5406A of PSU; 11st-12nd April for 1712 of Sc SWU and 18th-19th May 2016 for SNP3 of Arch KKU. The measurements of the last two cases were the repetition for error measurements during March. Unfortunately, the last classroom was measured at the end of semester. Occupied classrooms were not available during the measured period.

c. Calibration

In order to calibrate the cases in the very different conditions, a base case is required. The room AR207 of the main case study was selected to be the base case for these surveys and measurements. With the same feature and adjacent location, it was used instead of the previous base case (AR206) because AR206 was unavailable at the measured period. The satisfaction survey was also obtained for comparing the surveys of the additional case studies which were gotten in different times and places to each other and to the data in the previous survey in 2012. For calibrating the measurements, each case study was measured at the same time as the base case. The measurement results were compared to the base case to study differences. The long-term weather data obtained by weather station was used to verify the results.

3) Conclusion

This stage was included for to test applying the suggested solutions from the initial study to other classrooms in other regions of Thailand for generalising the research findings. For saving the research time, some of the additional cases studies were examined for their daylighting performance by comparing to modified cases. Due to the fact that only daylighting analysis was focused in this stage, DIALux was applied for this stage of the study. Some parts of results were also used in the stage of reflection analysis; therefore, they were analysed using the same format.

Chapter 4

Existing classrooms survey and measurement

Several types of surveys were selected in order to study existing classroom features which affect visual satisfaction and users' opinions. The surveys consisted of classroom observations, questionnaires, teacher interviews and measurements focusing on barriers to daylighting in classrooms such as light condition of the room and participants' satisfaction, and attitude in using natural light.

4.1 Classroom observation

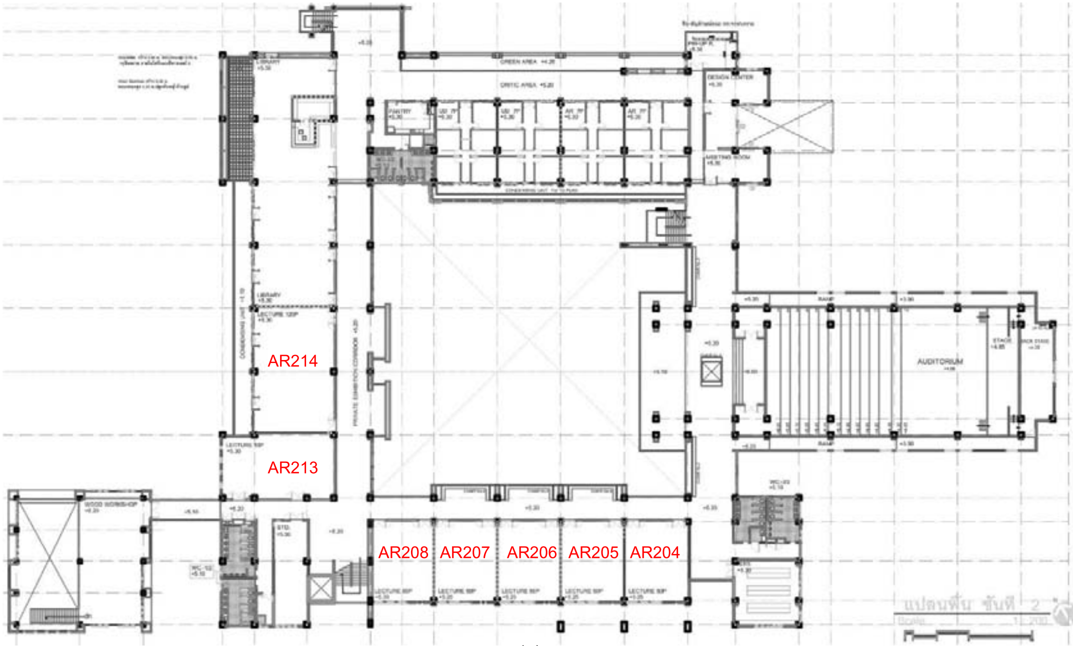
There are two points of observations, which are a basic survey of the classrooms and the users' behavior related to façade and system operation that can improve visual satisfaction. Observations were recorded as photographs and notes using observation form (see Appendix A).

1) Physical survey

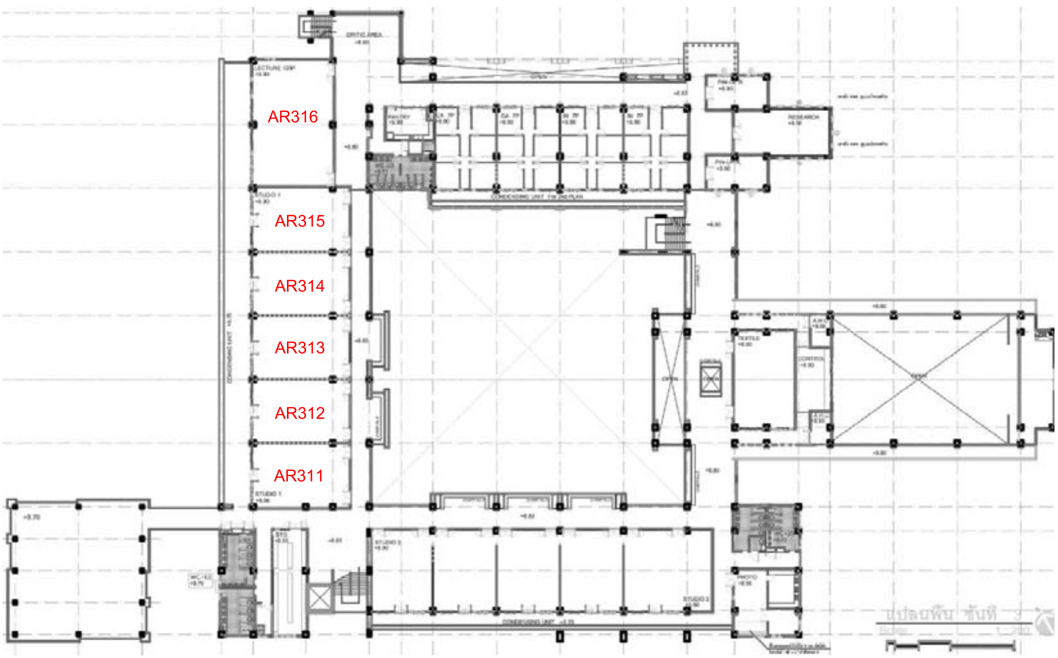
The Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University contains several types of educational areas, including lecture rooms. According to a comparison of physical surveys during June 2012 and December 2014, there were little changes in some rooms in terms of the arrangement of room furniture. The differences were probably considered to be insignificant as furniture can be moved easily at all times. As a result, the following results, based on the observations during June 2015, are reported here.

a. Layout and location

The studied building is located in the central area of the university. All faculty buildings were specified to be square in shape with a centre opened court. All classrooms are on the first and second floors. There are in total 13 classrooms, and the studied ones are 60-seat classrooms - room AR204-AR208 on the first floor and room AR311-AR315 on the second floor (see Figure 4.1 and 4.2). The building approximately faces to intermediate directions as can be seen in Figure 4.1 that the building rotates clockwise 36 degrees from north-south axis. It causes the classrooms on the first floor face to southwest and the classrooms on the second floor orient to northwest.



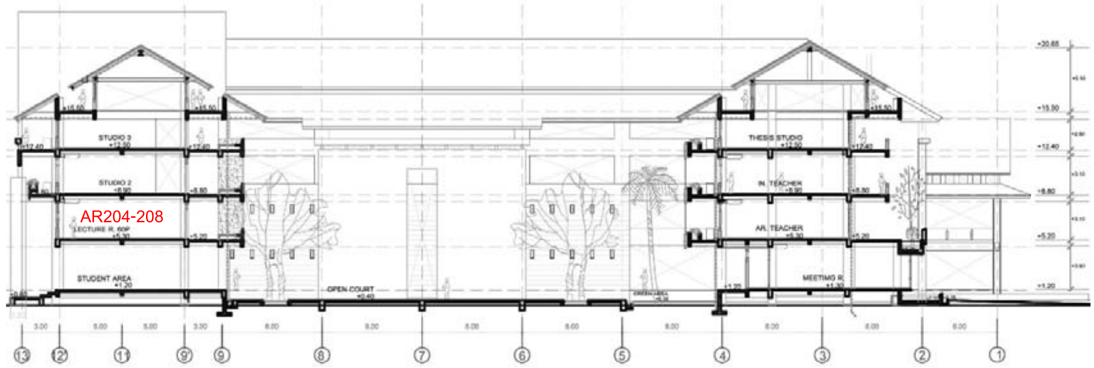
(a)



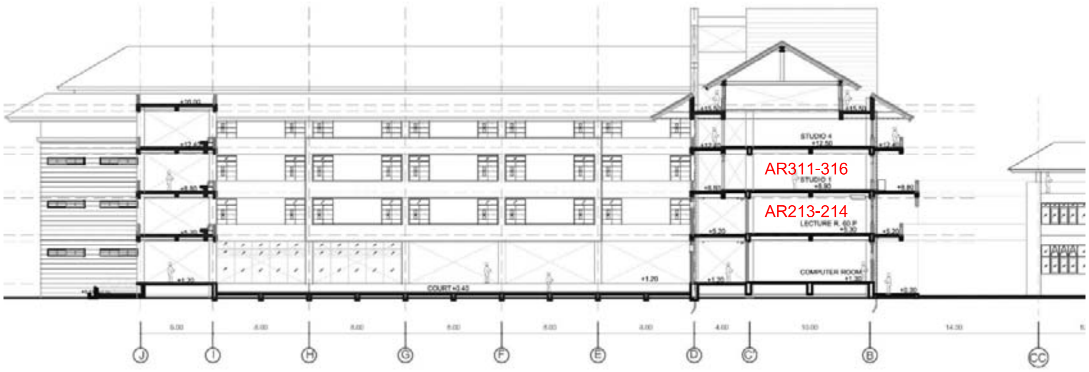
(b)

Fig.4. 1 Building floor plans show the positions of all lecture rooms: AR204-208, AR213-214 and AR311-316 which located on the first and second floor. (a) first floor plan and (b) second floor plan.

Source: As-built construction drawing of Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University.



(a)



(b)

Fig.4. 2 Building cross and longitudinal sections show the positions of all lecture rooms: AR204-208, AR213-214 and AR311-316 which located on the first and second floor. (a) Southwest to northeast section and (b) Southeast to northwest section. Source: As-built construction drawing of Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University.

The building is raised 1.20 metre above the ground. The first floor is 5.20 metre from the ground while the second floor is 8.80 metre above the ground.

b. Building envelope and surroundings

The southwest orientation of the building has a large green walk way which contains concrete footpaths, grass areas and many types of trees. The opposite building of the walk way, which is illustrated in Figure 4.3(a), is five story building located 63 metre far from the case study. The windows of the southwest classrooms have two main shading elements - about 10 metre high Fountain trees and shading (shown in Figure 4.3(b)). There are two surroundings which probably influence daylighting for the northwest orientation (see Figure 4.3(c)). At 15.50 metre away, the culture workshop building can be a light obstruction, but it is a two story building whose high is lower than the case study second floor room. Although the higher building is four-stories in high, the distance is 43.43 metre. Other surroundings, such as the wood workshop and nine-story building in the west shown in Figure 4.3(d) are not in influential positions for the southwest and northwest windows.

Fig.4. 3 Elements outside classroom window (a) building in opposite side of university greenery walk way by southwest orientation, (b) southwest sun shade consists of a row of Fountain Trees and overhang, (c) balconies in northwest orientation work as building shade while the nearby buildings are either lower or far, and (d) view from second floor classroom balcony to wood workshop. Other surrounding buildings are too far away to affect the entry of natural light into the classrooms in terms of obstruction and reflection.

Fig.4. 4 Façade feature of corridor side (a) corridor and sitting area, and (b) view from central court to class room corridor which palm trees and ornamental climbing plants are included

Fig.4. 5 Central court of the building (a) the large bright white wall, and (b) view from southwest classroom corridor to northwest wing of the building

On another side (Figure 4.5) a covered classroom corridor acts as the classroom shading device. It is a 2.40-metre-deep corridor with a two metre deep of columns with sitting area and planters between columns. The corridor was painted green and covered by ornamental climbing plants. The corridor faces to the central open court of the building which is 31.40 x 35.70 square metres. The court is surrounded with corridors and balconies in other wings of the building. The pavement is an exposed aggregate finish decorated with concrete and granite tiles. There are palm trees and their high is about two or three building stories. These trees have less impact in terms of daylight obstructions. The high of the building, the width of the court and the large area of bright white wall in the northwest building wing allow the occurrence of direct sun effects. Although it is great deep of corridor, the direct sunlight and excessive bright reflections off the wall and will probably influence the classroom.

c. Existing façade

For the typical classroom characteristic of the case study, there are two opposite sides of classroom wall that can be considered parts of the building envelope.

Firstly, the outside facing wall consists of a window and shading devices. The 2.10 metre deep continued balcony of the upper floor with its 0.60 x 1.20 metre supported columns function as shading devices for the window (Figure 4.6(a)). The window is one metre high from the room floor. It is adjacent to the column at the back of the room and the room concrete beam. As shown in Figure 4.6(a) and (b) there are a set of nine separated aluminum frame awning windows which are 4.6 metre wide and 1.80 metre high in total.

The glazing is normally coated with dust. The average transmittance of the dust covered glazing is 87% of the clear glazing (the different appearances are shown in Figure 4.6(c)). Fabric curtains with hand operated track are the internal shading device of the window. It is orange colour and translucent (see Figure 4.7(a)). It appears, in Figure 4.7 for instance, that the natural light affects the room both when the curtain was opened and closed. In the rest area of the wall in the front of the room, there are some small fixed windows sized 0.40 x 0.40 metre in some classroom. For example, Figure 4.7 presents three of them in AR206. They are probably not significant in terms of daylighting as they are normally closed by opaque plastic board.

Fig.4. 6 Existing window (a) view from outside, (b) maximum angle of opened window, and (c) comparison of clear glaze to general condition: coated with dust.

Fig.4. 7 Orange fabric curtain with hand operated track (a) partly closed condition, and (b) fully opened condition.

Fig.4. 8 Two wooden doors with fixed glazing connected to building corridor (a) view from corridor, and (b) the daylight transfer from an eyehole and a top window of each door.

On the opposite wall there are two sets of apertures. It is double casement doors with a top fixed glazing. The door height is two metres and 0.40 metres for the glazing. Their width is 1.68 metres. The door and its frame are made of wood. It is a 0.60 x 0.15 metre with a viewing panel on one side of each door set. Not much natural light enters the room from the doors. However, there is an unexpected negative effect resulting from some of the viewing panels. The large white wall in the court cause excessive bright reflection, mainly in the morning as it is facing southeast. It sometime causes indirect glare for teachers through an viewing panel. In Figure 4.8(a), for example, the white paper was used to shade the viewing panel in some rooms.

d. Room interior and systems

The classrooms are eight metre wide, 10.40 metre in length and 3.40 metre high. The considerable depth of the room can also results in difficulties for daylighting.

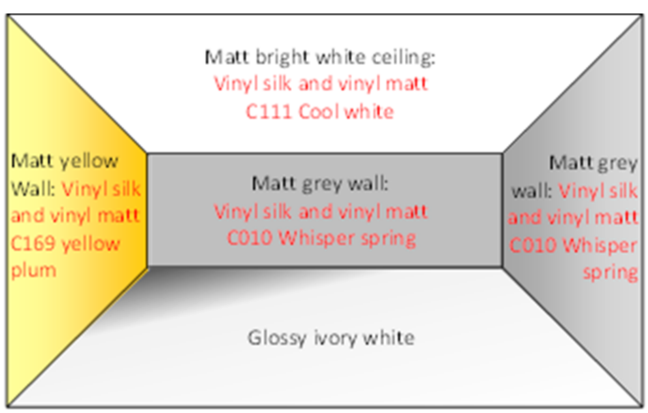


Fig.4. 9 Colours of walls, ceiling and floor painting

Fig.4. 10 Feature of lecture desks in the rooms: (a) AR205, and (b) AR206

Various colours were specified for room walls, ceiling and floor as shown in Fig.4.9. The ceiling, including structural concrete beams, was painted with matt bright white colour. The floor colour is a glossy ivory white. Matt yellow colour was used for the front wall while it is matt gray for the rest. The seats are made of various colours of plastic while the writing boards are foldable and made of plywood with a white glossy finish. The same colour of chairs was assigned into one room such as are shown in Figure 4.10(a) and (b) respectively: light brown in AR205 and yellow in AR206. Although the classrooms were designed for 60 students, 72 seats were generally placed in the rooms.

Fig.4. 11 Classroom systems: (a) projector, screen and control desk, and (b) lighting and other systems at the room ceiling.

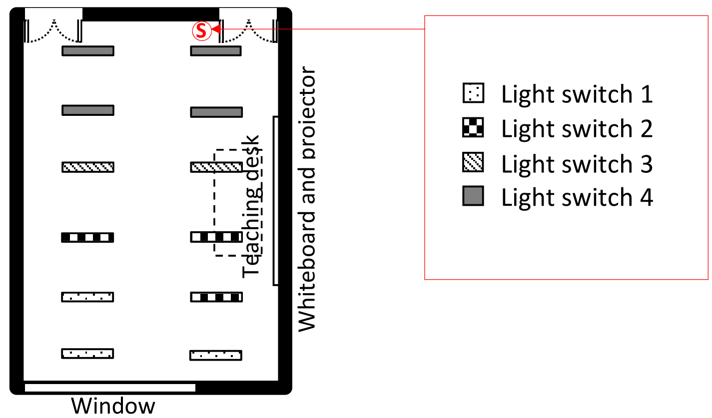


Fig.4. 12 Lighting lay out and groups of control switches of the room AR206.

The main teaching devices are a whiteboard and a projector. The whiteboard was placed at seating eye level along the length of the front wall. It is glossy white material for writing in the area in the middle, adjoining matt white small pin boards on both its sides. The projector screen is matt white and located in the middle of the front wall above the whiteboard. It can be applied over the whiteboard as demonstrated in Figure 4.11(a) by a manual roller while the projector was hung in the manufacturer's recommended position from the ceiling. There are two teaching desks at the front of the room (see Figure .4.11(a)): a glossy white finish table and a matt light blue controlled desk. The controlled desk contained a computer, 20 degrees tilt computer screen, and the switch board of computer and projector. The systems breaker and lighting switches are not included in this desk. They are located in other walls on the left and right hand side of teachers respectively.

Two 36 watt super TL-D fluorescent bulb and, 12 of aluminum mirror reflector pendant mouthed lamp were specified for the classroom lighting (see Figure 4.11(b)). Three of them were in the middle of the structural beam cavities. As presented in Figure 4.12, the lamps were divided into four separate controlled switches paralleling to window line. The switch board is nearby the front door.

Other building systems consist of air conditioning system (AC), speakers, fire alarm and sprinkler. The AC is two split type 10 kW air conditioners. Their condensing units are outside the room while the 0.6 m^3/s fan coil units are ceiling mounted type placed above the window. There are four speakers at the centre of each beam cavity and two photo electric smoke detectors below the main beam. They and their wires are either painted or originally in white colour. Two sets of upright sprinkler heads and their ducts were hanged from the ceiling to under beam level. The ducts were painted in red colour. Obviously in observation, it is not only the beams but also the systems leading to less diffusion efficiency of the ceiling despite being in very bright white colour. It is due to the fact that they cause many shadow areas for ceiling cavity. Apart from this issue, the systems probably have no significant effect on daylighting in the classrooms.

2) Classroom activities and system operations

During June 2012, various modules were randomly observed 24 times in the two studied classrooms, AR205 and AR206. Concerning daylighting, the system operations observed were room curtains and artificial light. The curtains were normally closed while the light was always switched off before the beginning of the classes. It was found that the major reason for switching on or off the light was to change teaching media, for example the light will be turned off if the projector is needed while switching on for using whiteboard while the curtain was not frequent operated unless the electricity was out of order or when the window was opened for applying natural ventilation in the winter, according to the other observation during December 2014. Figure 4.13 illustrates example of various activities: such as pinning-up, reading and taking note, class seminar, applying the projector, writing on the whiteboard and mixed use of the devices. Lighting conditions of the classrooms for each activity are also presented. With integration of teachers' interview, the classroom activities can be classified in to two main groups of activities: activities which lighting control is required and activities that probably apply natural light.

Due to fluctuation of natural light and of limitations of the teaching media, fully window shading combining with artificial light application is the main conditions in order to control the light. Activities in the first group focused on teaching devices, which are the projector and whiteboard. It can be considered as three activities: projector use which is general case in most classes, whiteboard use in some modules that demonstration of calculation or free hand drawing is necessary, and combination of using projector and whiteboard. In order to confirm needs of daylight in this type of activities, the curtain was intentionally opened every time before starting classes. As expected, the curtain was always closed before starting the classes. It is because a dim environment is required for using the projector. During the classes, the curtain was still closed despite the fact that the brighter condition was needed for other activities such as using whiteboard or briefing of hand-outs. In general, the classes normally used only one device which was a projector. The light was operated four times at the beginning and the end of the classes and of the use of the device use (the sequence is shown in Table 4.1). When applying a projector, the light might be switched off in some classes but it was partly switched on for students' note taking. The light will be switched twice, at the beginning and the end of the classes when using only whiteboards. On the other hand, it was more frequent in various activity modules, for both projector and whiteboard use including reading and practicing activities for instance.

Fig.4. 13 Example of teaching activities (a) pin-up session, (b) hand-out reading in an assignment brief, (c) application of visual media lecture, (d) seminar, (e) students brain storm using whiteboard, and (f) combination of projector and whiteboard use.

However, lighting operation can vary depending on the teaching habits of each teacher. Using the projector as the only device, some teachers preferred to operate lighting more than four times for handing out an assignment, general talking and taking a break for example.

Tab.4. 1 Sequence of classroom activities and their lighting applications for the activities that lighting control is required.

Teaching behaviour	time		before class		9.00	9.15	9.30	9.45	10.00	10.15	10.30	10.45	11.00	11.15	11.30	11.45	12.00	after class
					13.00	13.15	13.30	13.45	14.00	14.15	14.30	14.45	15.00	15.15	15.30	15.45	16.00	
General behaviour	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Taking a register of the students/ introduction			teaching (using projector and/or visualizer)								talk/ hand out	class over	unused room
	system operation	light	off	on	on			partly on								on	off	off
		curtain	close	close	close			close								close	close	close
		A/C	off	on	on			on								on	off	off
Whiteboard is the main device in some module e.g. Calculation, sketch	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Taking a register of the students/ introduction			teaching (using whiteboard)								talk/ hand out	class over	unused room
	system operation	light	off	on	on			on								on	off	off
		curtain	close	close	close			close								close	close	close
		A/C	off	on	on			on								on	off	off
Projector and whitboard use	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Taking a register of the students/ introduction			teaching (using projector)		whiteboard use	teaching (using projector)		whiteboard use	teaching (using projector)		talk/ hand out	class over	unused room
	system operation	light	off	on	on			partly on		on	partly on		on	partly on		on	off	off
		curtain	close	close	close			close		close	close		close	close		close	close	close
		A/C	off	on	on			on		on	on		on	on		on	off	off

Source: Supansomboon and Sharples (2013)

Tab.4. 2 Sequence of classroom activities and their lighting applications for the activities that natural light probably apply.

Teaching behaviour	time		before class		9.00	9.15	9.30	9.45	10.00	10.15	10.30	10.45	11.00	11.15	11.30	11.45	12.00	after class
					13.00	13.15	13.30	13.45	14.00	14.15	14.30	14.45	15.00	15.15	15.30	15.45	16.00	
Student pin-up	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Taking a register of the students/ introduction			Student pin-up (normally at the front board, sometime at other walls)								talk/ hand out	class over	unused room
	system operation	light	off	on	on			on								on	off	off
		curtain	close	close	open			open								open	open	open
		A/C	off	on	on			on								on	off	off
Specific module e.g. seminar	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Class check/ introduction			present-ation		seminar						talk/ hand out	class over	unused room
	system operation	light	off	on	on			partly on		on						on	off	off
		curtain	close	close	close			close		open						open	open	open
		A/C	off	on	on			on		on						on	off	off
practice module	sequence of activities		unused room	classroom preparation (5-15 minutes before start)	Class check/ introduction			teaching (using projector)				talk/ hand out		student practice			class over	unused room
	system operation	light	off	on	on			partly on				on		on			off	off
		curtain	close	close	open			close				close		open			open	open
		A/C	off	on	on			on				on		on			off	off

Source: Supansomboon and Sharples (2013)

There are some activities that the users probably apply natural light in to the room, such as student pin-up, seminar and some practice modules like rough sketch designs. For these kinds of activities, the variation of natural light is acceptable. Table 4.2 shows example of activity sequence that the light was usually switch on while the curtain was also opened when those activities start. When the classes start with opened curtain, the users decided not to close the curtain in some classes. It is interesting that some teachers and students intended to use natural light by opening curtains when class activities are drawing practice and pinup.

In order to operate classroom façade and lighting systems, the teachers were generally the main operators. The students were frequently commanded to be the operator because the system controllers were far away from where the teacher stood. However, they sometimes requested for better brightness conditions or they were implicitly allowed to operate the systems in pinup and drawing practice class as they involve with the activities more.

3) Visual issues

According to observation, there are three daylighting issues. Firstly, the existing facade transferred insufficient illumination levels of daylight into the classrooms in general. Artificial light was regularly integrated even in some casual activities which natural light is a users' preference, such as a seminar. It might because the illumination was too low, especially in areas further away from the window and excessive high contrast between maximum and minimum illumination. Secondly, the dimmest environment appears not dim enough for seeing the projector. The main reason is translucent light transferring from the curtain. This translucent light sometime led to indirect glare and its orange colour may cause an orange colour cast (shown in Figure 4.14(a)), possibly leading to colour perception problem. Lastly, veiling reflections occur on the whiteboard, particularly in the afternoon classes. As shown in Figure 4.14(b)), it is caused by reflected light on the glossy surface of the whiteboard from two sources - the window and the fluorescent lamps,

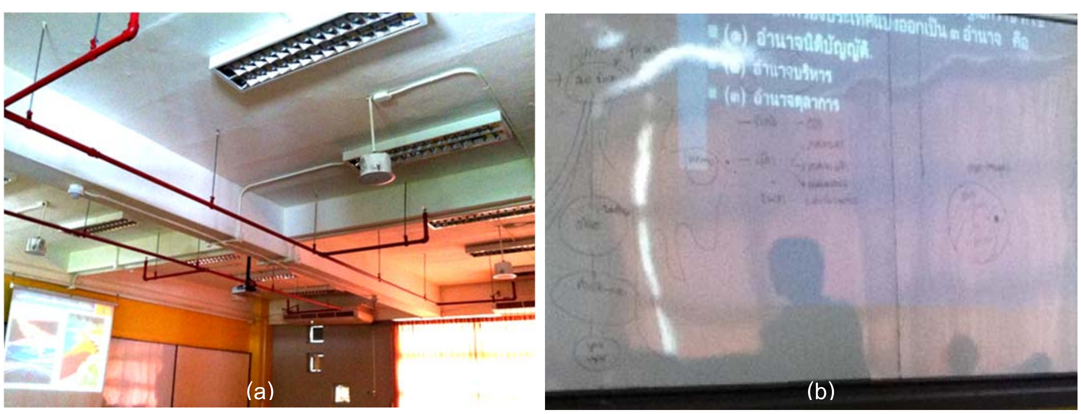


Fig.4. 14 Visual issues which were raised from building users: (a) orange transmitted light effect through the curtain, and (b) excessive bright environment for seeing projector and problem of veiling reflection on whiteboard.

In the case of insufficient illuminance, the main reason is possibly the size of the room, which is very wide. The normal single side window might not be able to bring sufficient daylight to the furthest part of the room and it might also lead to high contrast compared to the very high illuminance near the window. In addition, there are many elements of building structure and systems that can be obstacles to daylight diffusion. When the façade was studied, it appeared that an insufficiently small overhang probably causes a serious problem due to the direct sun while the curtain seemed improper in terms of its colour and opaqueness.

Apart from visual problems, a conflict of illuminance requirement was also one of the difficulties. The light level needs for each activity are extremely different, bright for seeing whiteboard and note taking while dim for using projector. The light environment was required to be changeable. The class participants either selected to switch the light on or accepted those improper light levels.

4.2 Users' opinions

The building users consisting of students and teachers were questioned regarding their satisfaction, room operation behavior and attitudes in terms of applying daylight. This was done in order to confirm the actual visual problems which related to lighting quality of their classrooms. The teachers were interviewed using the interview question list (see Appendix A: interview script) while questionnaires (in Appendix A: Questionnaire 02) was distributed to students by random.

1) Room environment satisfaction

During June 2012, satisfaction questions were asked to most of the classroom users, not only about visual environment satisfaction but also thermal and general aspects. Two groups of participants, teachers and students, indicated slightly different opinions.

Apart from illumination, what the users thought about their classrooms in other aspects was also examined in order to avoid generalization. Figure 4.15 shows three data set of participants' satisfaction and sensations: overall satisfaction, sensation in terms of lighting levels and thermal comfort. The range on the x axis can be either 'very high' to 'very low' satisfaction rate of the room or 'very high' to 'very low' levels of lighting and temperature depending on the lines. For overall satisfaction, 'satisfied' was voted for by the majority of participants (~about 50%). Almost 30% thought they were 'slightly satisfied' with their classrooms. About 40% of participants rated room temperature as 'comfortably cold'. 33% of participants thought it was comfortable. Due to hot climates, the air conditioning system was usually applied when the classrooms were in use; therefore, room temperature was generally rated comfortable. For illumination, 'bright' condition was rated by a majority for about 60% of participants. 'Slightly bright' and 'neither bright nor dim' were next at about 19% and 15% respectively. In other words, the majority thought that their classrooms were generally 'Bright', 'Slightly cold' and they were 'Satisfied' their classrooms in general. From these results, it is possible that neutral to cold and bright are the preference conditions that the participants want for their classroom.

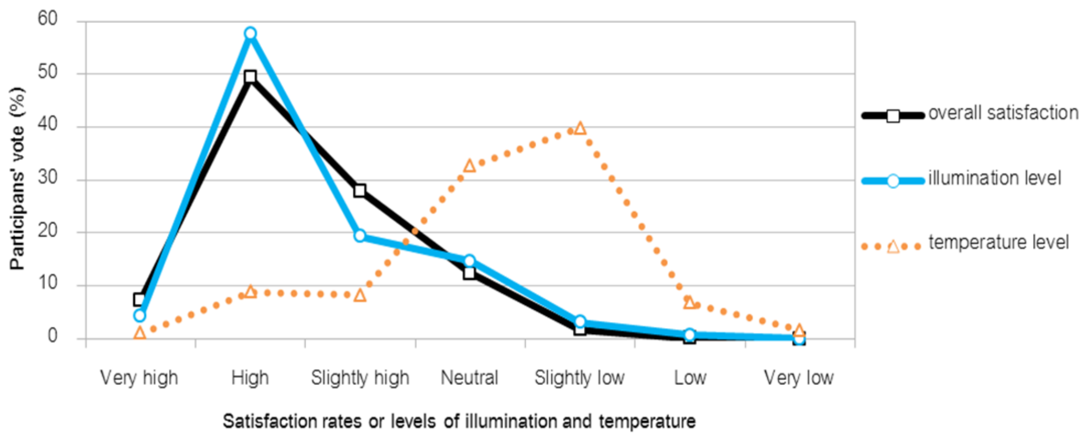


Fig.4. 15 Survey of classroom satisfactions.

In terms of illumination level in general, most of the students thought their classrooms were *'bright'* more than *'neither bright nor dim'* and *'dim'* respectively (see Figure 4.16(a)). For the teachers (shown in Figure 4.16(b)), the numbers of participants who thought their classrooms were *'bright'*, *'neither bright nor dim'* and *'dim'* were almost equal. The dim conditions might be because there is no window at the teachers' area, in addition, teachers normally face opposite to the projector screen, which become a main light source when both the lights and curtain are off. However, the teachers rated *'bright'* condition little more than the other conditions, which possibly show agreement with the students' opinion. In order to examine their satisfaction, they were questioned whether the general brightness conditions were acceptable or not. The results presented in Figure 4.17 show that almost all of the students and teachers agreed that it was *'acceptable'*.

According to the interview, it was found that the teachers appeared to be undecided. It is probably because there were two different common conditions, switching on and off artificial lights. The illumination level was mainly rated as *'slightly bright'* and *'bright'* when the light was turned on. When it was turned off for using the projector, the room environment was too dim for students to take notes. Turned-off lights for using the projector and turned-on light for other activities appeared to be their preferences since some of them said it was the best conditions in the classrooms which they had.

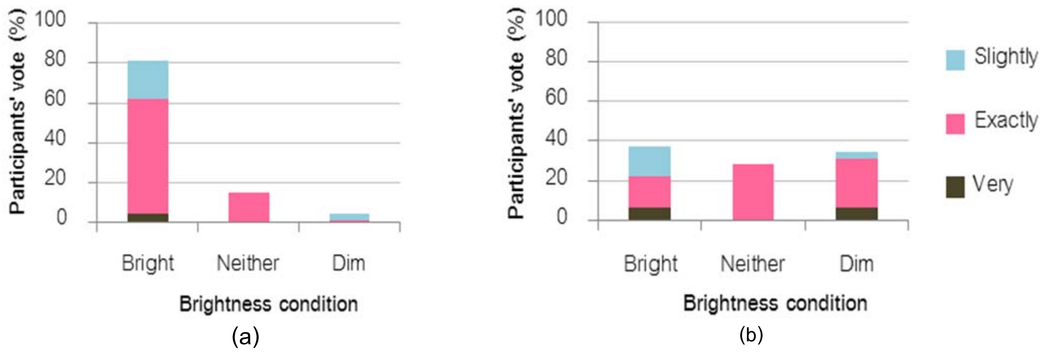


Fig.4. 16 Brightness conditions in perspective of (a) students and (b) teachers

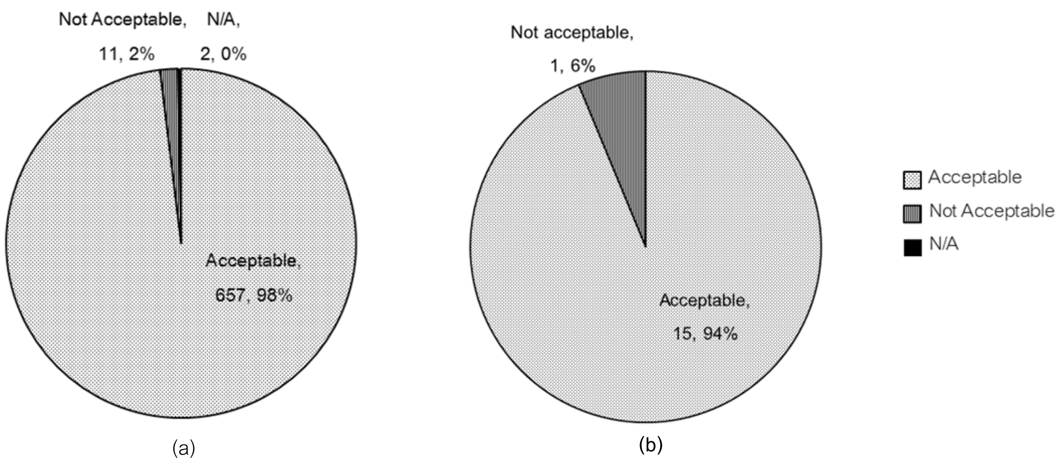


Fig.4. 17 Classroom brightness satisfaction of (a) students and (b) teachers

For the visual satisfaction of the students, this survey focused on three viewing tasks: lecture desk, whiteboard and projector screen. The conclusion is shown in Figure 4.18(a). The lecture desk appeared to be the most satisfying device since the student rated that ‘satisfied’ (58%), while a few students were dissatisfied when taking notes at their desk. The main issue of dissatisfaction was insufficient brightness because the light had to be switched off when the projector was utilized. On the other hand, the reasons for satisfaction can be various. The students may claim that they were satisfied when the light was turned on in some cases, for example when the teacher assigned them to revise the lesson or when an assignment was handed out. It is possible that it is unnecessary to take notes because PowerPoint material had already been distributed. Furthermore, students might prefer not to take notes as some of them gave information in the questionnaire that they preferred the dim environment which can make them satisfied when sleeping.

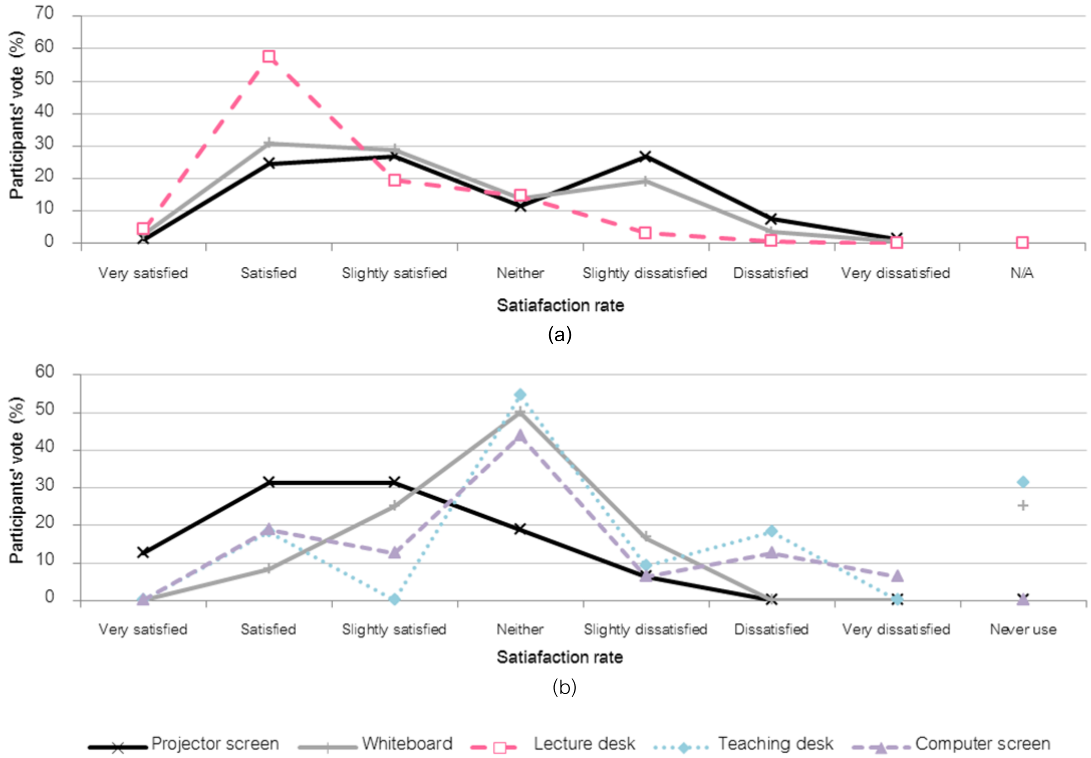


Fig.4. 18 Visual task satisfaction of (a) students and (b) teachers

In the case of the whiteboard and projector screen, there was both dissatisfaction and satisfaction. Although most of the students said they were either *'satisfied'* or *'slightly satisfied'* with their classroom, noticeable numbers of the students were *'slightly dissatisfied'*. Dissatisfaction with the projector screen was more than for the whiteboard.

The students commented that the brightness was optimal for using the whiteboard when the light was switched on. Apart from the size and position of the board, the most significant problem was veiling reflections from its glossy surface. According to the survey, the veiling reflection at the whiteboard was frequently brought about by two light sources. The first source was side lighting from the window. It is pointed out that existing façade could not control fluctuations of natural light, neither when the curtain was opened nor closed, and this led to discomfort glare and veiling reflections, particularly from the low angle of direct sunlight. Lastly, direct glare usually occurred on the board when the projector was sometimes applied without its screen. The problem might be because the whiteboard was in the same position of the projector screen and it was essential to use the whiteboard and the projector at the same time.

Unclear projecting images appeared to be the main issues when seeing the projector screen. Most of the participants who were dissatisfied with seeing the task confirmed that both the artificial light and the natural light affected the task. Although the best solution was switching off the light and closing the curtain, translucent light from the window could sometimes cause glare and had negative effects on seeing the images. In order to reduce that effects and allow them to take notes during lectures, some of the participants suggested that the layout of light switching should be divided into the front and at the back of the room instead of the nearest and the farthest to the window. However, it is noted that the low quality of the projector device could be another reason for dissatisfaction.

In conclusion, the participants were, in general, satisfied with their classrooms. In their opinion, the classrooms were normally bright and comfortable. The main difficulties for visual comfort were a lack of control of daylight and improper lighting systems when using the projector while taking notes and also when the whiteboard and projector were applied together. Other comments from the students implied that other aspects which had not been asked, such as the condition of the lecture desks or air conditioning system, may be ranked as the priority in terms of comfort evaluation. Therefore, it is possible that their satisfaction of the visual environment was only relative when compared to other aspects of the classroom environment.

For the teachers, teaching desk, whiteboard, projector screen and computer screen were the main concerns. There are different results for teachers' satisfaction as it shown in Figure 4.18(b).

31% of participants never used the teaching desk for visual purposes, while 55% of the users' opinion is *'neither satisfied nor dissatisfied'*. The number of dissatisfied is more than those satisfied even if most of them had rarely used the desk. The task was frequently in low illumination level because the window had less impact on its area and the required condition for the front of the room was normally dim for using projector. Related problems of using the desk consisted of its improper size and position which obstructed students' view of the board. In addition, the positions of teaching device and controller were not supportive.

25% of interviewees said they never used a whiteboard for several reasons, whereas a half of whiteboard users were *'neither satisfied nor satisfied'* with the device. Conversely, the proportion of satisfied comments was dramatically higher than dissatisfied. One of the whiteboard utilization difficulties was also its size and position. As it was applied together with the projector, it is pointed out that one-third of its area was obstructed by the projector screen resulting in insufficient available area to write on. Additionally, participants said that the glossy surface of the board frequently led to veiling reflections which caused students' visual difficulties.

A large proportion of interviewees, 75%, was satisfied with the projector screen while only one person was slightly dissatisfied. Most of the comments involved the low quality of the projected images, such as distort colours, clearness and brightness. They required the device to be improved particularly for use in daylight. In terms of seeing problems, they implied that it relied on sitting position of the student including furniture and devices arrangement. Because the views of students in the back of the room were obstructed by other students and the teaching desk, the screen was suggested to be larger and set in the higher level. However, it is noted that teachers were not the principal users of this device resulting in the information collected might be secondary data which was received from students.

Most of the participants thought the computer screen was *'neither satisfactory nor dissatisfactory'*. That proportion is slightly higher than satisfied and dissatisfied respectively. The major issue of the device was its 30 degrees tilt resulting in inconvenient seeing for both sitting and standing. Some of interviewees pointed out that it was veiling reflection on the device.

To sum up, participants were generally satisfied with the brightness environment of their classroom mainly using artificial light. Natural light was their preference, but its fluctuation appeared to be a problem. Existing control systems were not able to meet the illumination requirements and inconvenient to apply while teaching. Focusing on substantial devices, most of the teachers felt *'neither satisfied nor dissatisfied'* excluding the projector screen, which was not their main seeing task. Moreover, the interviewees provided other issues which may affect visual comfort in the classrooms. Because of reflections from the white wall in the court, glare occurred through the small apertures of room doors or when a door had been opened, especially in a dim environment for projector use. For the classroom appearance, apart from irritating orange colour of the inside wall in the front of the room, room shape also appeared to be problem. The excessively wide room dimension meant the students who sat at two sides of the front row could hardly see the projector screen

Apart from conflicts of illumination requirements, the results of classroom users' satisfaction survey reveal problems in more detail. Firstly, the occupants preferred bright condition when artificial lighting was applied for general classroom activities. Dim conditions were also the preference for using the projector, but it seems that the switched-off the light was just the best solution which they had experienced. Curtain operation has never been solution for illumination improvement. Moreover, translucent light through the curtain frequently caused glare and veiling reflection. Improperly controlled systems such as lighting layout and switch board position appear to be one of the problems but the difference opinions between teachers and students can be a more serious issue. Teachers were the key people who operated all systems in the room while their opinions about light environment of the room are more neutral than students'. It probably means if students do not point out that they are not satisfied, teachers will neither realise the dissatisfaction nor improve that unpleasant condition.

2) Occupants' attitude vs. their behavior

In order to apply daylight in the classroom, users' opinion is one of important aspects that can confirm their daylight requirement. Theoretically, many pieces of research confirm that using daylight leading to positive effect on students' learning performance. Daylight is not practically applied into rooms as much as its availability. In order to study the issues, users were questioned about their attitude in using daylight and their behaviour regarding façade and lighting control. Expectedly, the results show conflicts between attitude and behaviour that can be one of daylighting barriers.

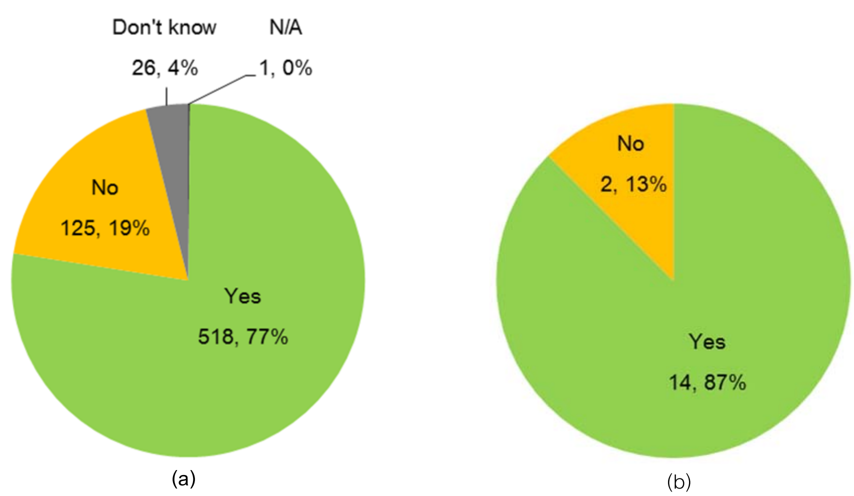


Fig.4. 19 Attitude of using daylight of (a) students and (b) teachers

Most of the students, 77% of participants, thought natural light benefited their learning performance and motivation (see Figure 4.19(a)) although it appeared from observations that they had not frequently used the daylight. Around 19% of the students thought daylight had either no effect or negative effect on their study, and approximately 4% could not specify their attitudes. 87% of teachers thought that natural light benefited the learning performance of the students (shown in Figure 4.19(b)). According to interviews, two of them who did not agree pointed out that natural light might disturb the classroom environment for not only seeing tasks but also the concentration of the students.

The results might not illustrate that the participants absolutely agree about the benefit of daylight on students' learning performance but none of participants thought it is harmful. There are three groups of comments provided by a minority. The most critical comment was disturbance of daylight resulting from fluctuations and the high intensity of natural light. Participants thought it is more difficult to control the daylight than using artificial light. Some participants thought daylight influenced the class activities in neither a positive nor negative way while the rest were not sure whether natural light benefits classroom or not. As a result, it is possible that the majority can be increased if the daylight could be practically controlled.

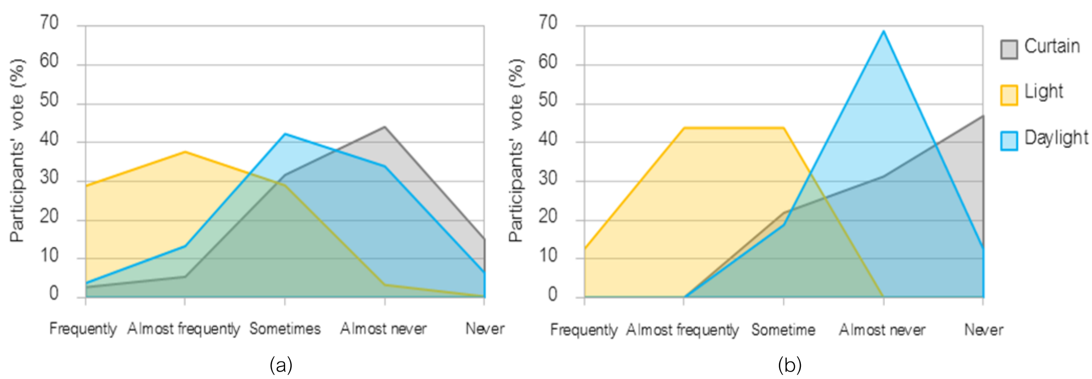


Fig.4. 20 Use frequencies of the curtain, the light and daylight in the opinions of (a) students and (b) teachers

The participants provided inconsistent information of their behaviour against their positive attitude in applying natural light. When the frequency of use of the natural and artificial light had been questioned, most of the students thought they *'almost frequently'* used the artificial light while they "*sometimes'* used the natural light in their class (Figure 4.20(a)). The use of the curtain appeared to influence the natural light use but the data implied that the use of the daylight was more frequent than the curtain since the majority of the students thought that they *'almost never'* used the curtain. It reveals that the participants realised the application of natural light even when the curtain was closed.

For teachers, it is obvious in Figure 4.20(b) that the result partly agrees with the students' in terms of more frequent of using artificial light than natural light. The most frequent reason was that while natural light was suitable for note taking or drawing practice, there was excessive brightness when using the projector and it was difficult to control. In the teachers' opinion, the difference between using natural and artificial light were greater than the students' opinion. Almost all of them informed that their lighting use was about half *'almost frequently'* and half *'some time'*. They also confirmed less frequent use of daylight by claiming that *'almost never'* use daylight and *'never'* use the curtain for 69% and 47% respectively.

The differences in their opinion are possibly because teachers are the principal operators of room systems; therefore, they could notice what they have done to improve light environment of the room. When observation was included, the teachers' pointed out the same results. The curtain was never opened in all cases that the class started with closed curtains. For the lighting, it might be supposed to be *'frequently'* used as the light was always turned on at the beginning and off at the end of the class but it is rather *'almost frequently'* and *'sometime'* because the main teaching media of the class is a projector which the light was needed to be switched off during using the device.

3) Suggested problems

Although their attitude in using natural light is obviously positive, the users preferred using artificial light and appeared to avoid daylight. One of the main reasons is the conflict of illuminance requirements: bright for general use and dim for seeing projector. Applying the daylight, the users stated that illumination level was insufficient in general even though the curtain was fully opened. For projector use, the curtain was required to be closed as well as the light, but the existing brightness conditions were improper. It is inadequate illuminance for note taking while excessive bright translucent daylight from the curtain sometimes caused difficulty for seeing projector.

The participants also raised the problems of indirect glare from the window and veiling reflection on the whiteboard. There were complaints that the southwest orientation classrooms normally had more disturbing brightness than that in northwest and it occurred in the afternoon more than in the morning. This is because of the effect of sun geometry on different window orientations. Due to its high intensity and low angle, direct sunlight critically influences windows facing southwest in the afternoon. The shading devices appear not only to be inadequate but also cause another problem. The translucent sunlight from the curtain brought about the disturbing orange coloured light.

Less frequently using natural light, the users suggested that the system operations were also a significant issue. Where lighting system was concerned, almost all of the teachers affirmed that its controlled switches had no system lead to controlled difficulty particularly for daylighting integration. Moreover, lighting positions were not suitable for class activities which normally used a projector. They suggested that the sets of lamps should be divided to the front and the back row for projector use instead of parallel to the window line. In case of natural light control, the curtain was required to be easier to control in order to integrate natural light into different illumination requirements. In addition, system controllers in the classrooms were located far away from the teaching stand. The students sometimes operated the systems themselves only for some practice activities while it is possible that the teachers either commanded students to do it or accepted that improper light environment.

4.3 Physical measurements

In order to study natural light distribution problems, weather data was measured in the case study. The classrooms: AR205 and AR313 were selected to be variable cases of façade and system. They were measured at the same time as AR206, which is the base case with a southwest orientation, closed the curtain and switched off light. The measurements were mainly taken from 31st May to 20th June 2012 which represented summer solstice. The winter weather was examined for additional data during 3rd – 26th December 2014 which contains the winter solstice. Analysis of the data focused on the class schedule which was commonly between 9AM and 4PM. The measurements aimed to give an overview of the classroom's environment and investigate the impact of existing façade parameters.

1) Weather data of the classrooms

Four HOBO loggers and a CO_2 Logger were applied to each room for collecting four categories of data: temperature, relative humidity (RH), illuminance and CO_2. Although the collection focused on illumination of the case studies, other data consisted of temperature, relative humidity and Carbon dioxide rate were included in order to examine general condition of room.

a. Outdoor weather overview

For the base case classroom in the southwest, temperature were lowest when the class was started, then rose to the peak, whereas the RH patterns were the inverse (see Figure 4.21(a), (b), (d) and (e)). Figure 4.21(c) and (f) show that the lowest illuminance was at 9AM and became higher in the afternoon. The maximum illuminances were generally between 2-3PM.

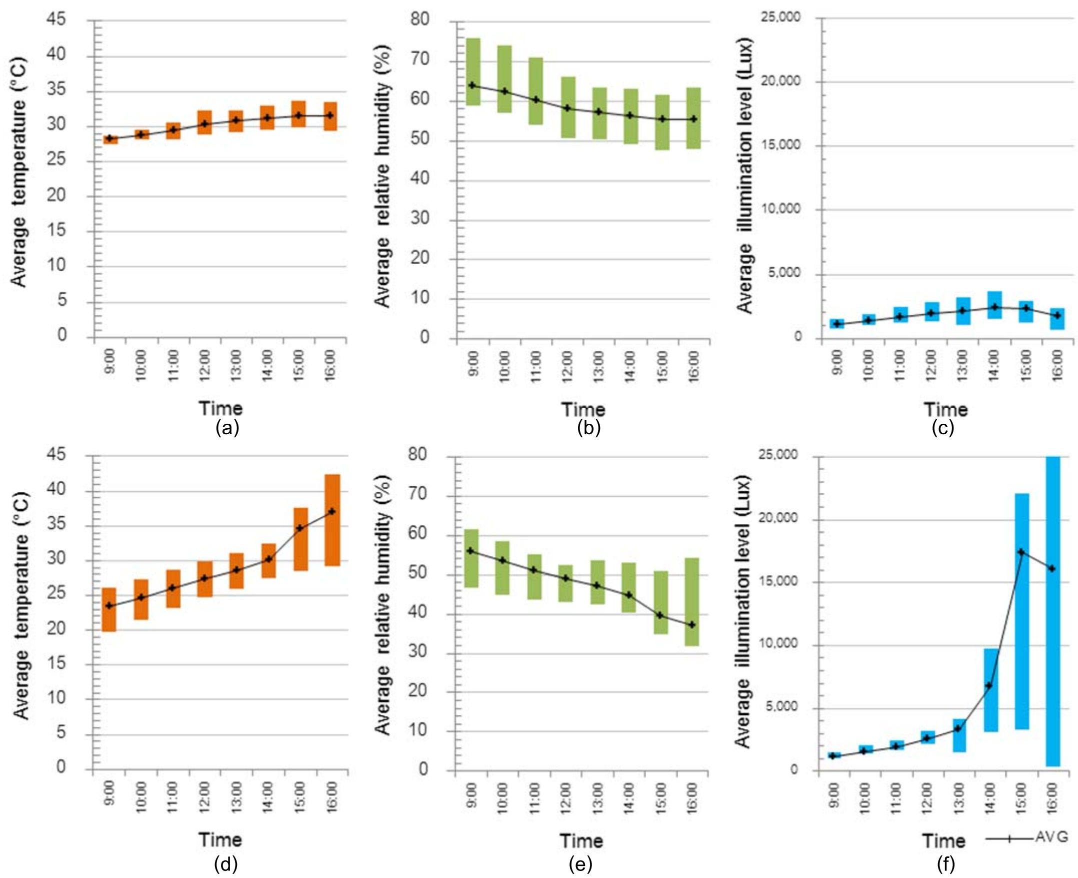


Fig.4. 21 Ranges and averages of outdoor temperature, relative humidity and illuminance (a)-(c) measurement during 31st May-20th June 2012 and (d)-(f) measurement 3rd – 26th December 2014.

The ranges of summer temperature were limited at 27-34°C while they were wider in winter at about 20-43°C (see Figure 4.21(a) and (d)). The biggest differences were at 4PM. The maximum range was as much as 15°C in winter. During the operated hours, summer solstice average temperature rates were, as expected, substantially warmer at about 28-32°C. For the winter solstice, average temperature rates approximated to comfort at about 24-27°C in the morning. Increasing rate then rose to maximum at 37°C. Surprisingly, temperature in winter which supposed to be lower was rather higher than summer particularly in the afternoon. It is due to effect of direct sun facing south in the afternoon winter. During the measurement period, RH ranges were about 50-75% for summer and 30-60% for winter (Figure 4.21(b)and(e)). Averages were 55-65% and 40-55% for summer and winter respectively. The higher RHs were in summer and in the morning. Differences of average minimum and maximum RH are approximate for summer and winter solstice. The ranges are about 10-20%: in summer it is steadier than in winter.

When compare to other aspects, direct sunlight had the most impact on outdoor illuminance shown in Figure 4.21.(c) and (f). While illuminance of summer solstice was in the range of 1,000-4,000 lux, it was about 500-25,500 lux for winter solstice. The extreme difference of winter illuminance was due to influence of direct sun on southwest window in the afternoon. On the other hand, summer illuminance was steady because the sun did not affect the window directly. Average illuminance was about 1,000-2,000 lux for summer while the winter illuminance reached ae peak at 18,000 lux.

b. Temperature

According to the measurement shown in Figure 4.22, ambient temperature of the case study generally reached a peak of30-35°C during 1–4PM both for summer and winter. It then reduced to 27-28°C or 18-19°C, for summer and winter respectively, at about 4-8AM. Where the room temperature was concerned, the hourly data in each measured point were more uniform than the outside. As is shown in Figure 4.22, the temperature at the positions HBI2 and BHI3 were steady when the room was not in use on 19th June 2012 and 21st-23rd December 2014 at about 29-30°C and 24-25°C respectively. The room was commonly closed, and this led to unchanged thermal conditions even though the outside weather was fluctuating. The temperatures at HBI1 position which was located near by the window were not significantly different in general while higher than that at HBI2 and HBI3 positions at the peak. There is about a 4-5°C difference for winter and slightly higher for summer. The differences were probably due to the influence of direct sun and radiation from the window.

The air conditioning system was regularly applied for all classrooms. The system was operated only when the room was occupied. During the measurement time, the AC was switched on only in the afternoon class on 18th and 20th June 2012 (Figure 4.22(a)). As for the impact of the system, the room temperature on 18th June decreased rapidly to 24-25°C after the class was started at 1PM. It is similar to the 20th June class, but the decrease is about to 25-26°C due to the shorter period of time. The rates of the temperature increased immediately since closing the air conditioning system when the classes were finished. Outdoor temperature also reduced for 1-3°C when air conditioning system was operated. It is because the HOBO logger was placed close to the window where the glazing has ineffective thermal resistance.

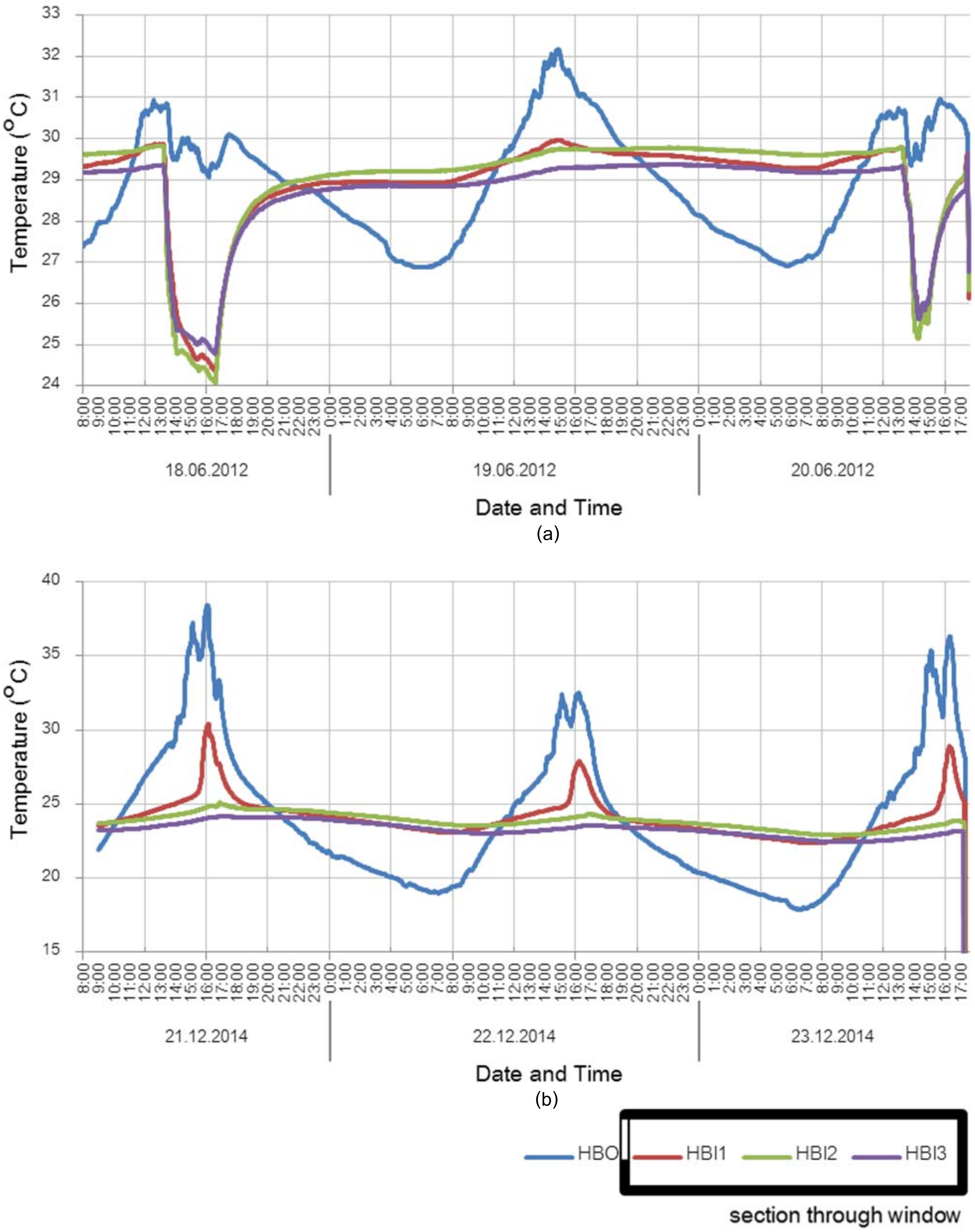


Fig.4. 22 Minutely temperature of AR206 collected during: (a) 18th-20th June 2012 and (b) 21st-23rd December 2014.

c. Relative humidity

As seen in Figure 4.23, outside RH patterns are normally the reverse of temperature. After it reached the maximum at 63-65% and 54-58% during 4-7AM for summer and winter solstice, RH fell dramatically to the minimum about 50% for summer and 33-35% for winter at 1-5PM. The graph then went up gradually to the highest level in the early morning. The room RH appeared to be steadier than outside especially when the room was not used while they approximated to each other during the night. Most of RH rates in closed room without air conditioning appeared to be steady at approximately 60-65% for summer solstice and 55-60% for winter solstice. During winter solstice shown in Figure 4.23(b), RH of the position nearby the window (HBI1) was about 5-10% lower than other positions at 4PM. It reveals influence of direct sun light on RH that RH can be reduced by effect of direct sun.

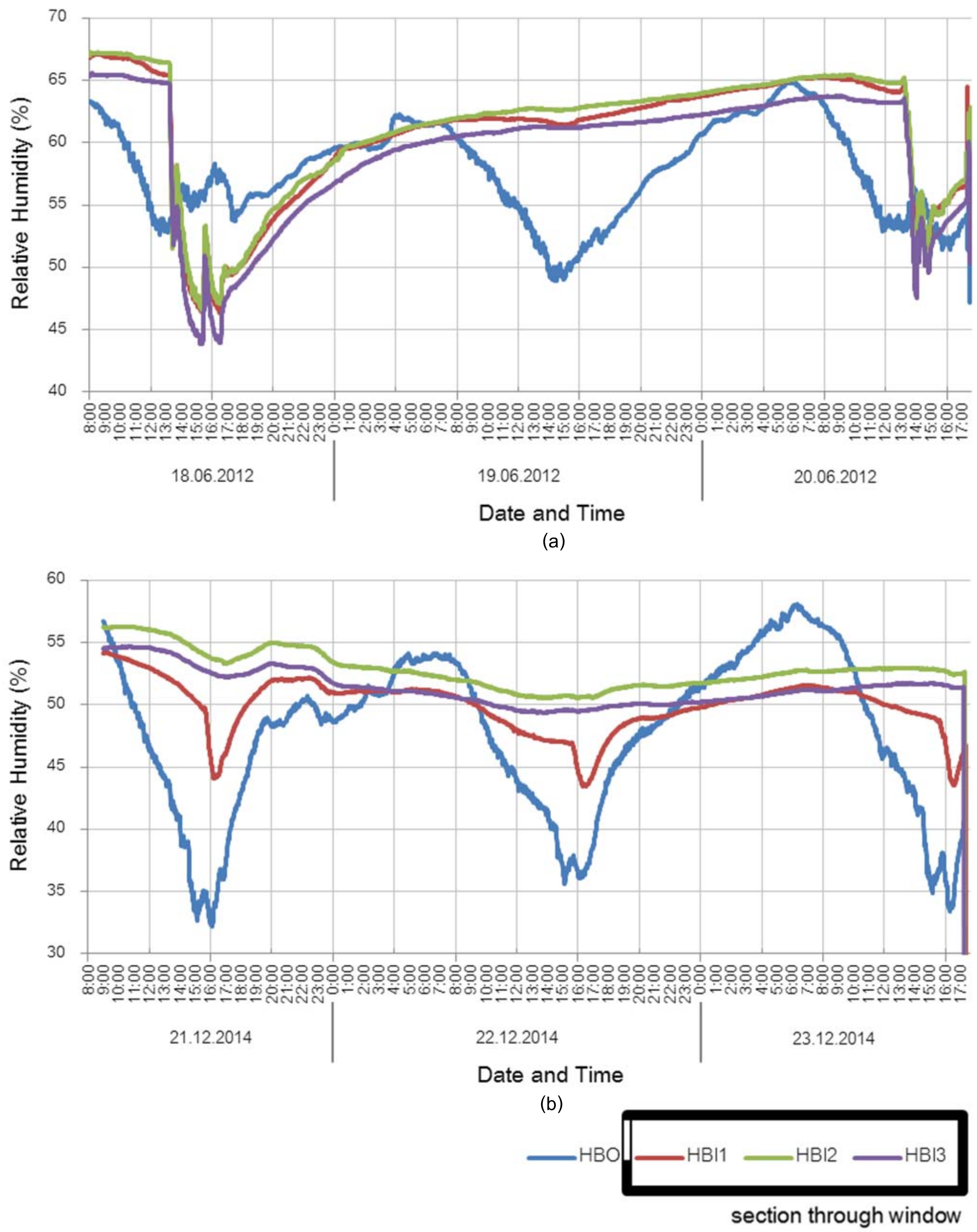


Fig.4. 23 Minute relative humidity values of AR206 collected during: (a) 18th-20th June 2012 and (b) 21st-23rd December 2014.

Changes of RH were also influenced by the cooling system. If the system was operated on 18th and 20th June in Figure 4.23(a) for example, the humidity decreased instantaneously to about 45-55%. After the class, RH also rose immediately until it was close to outside RH.

d. Light intensity

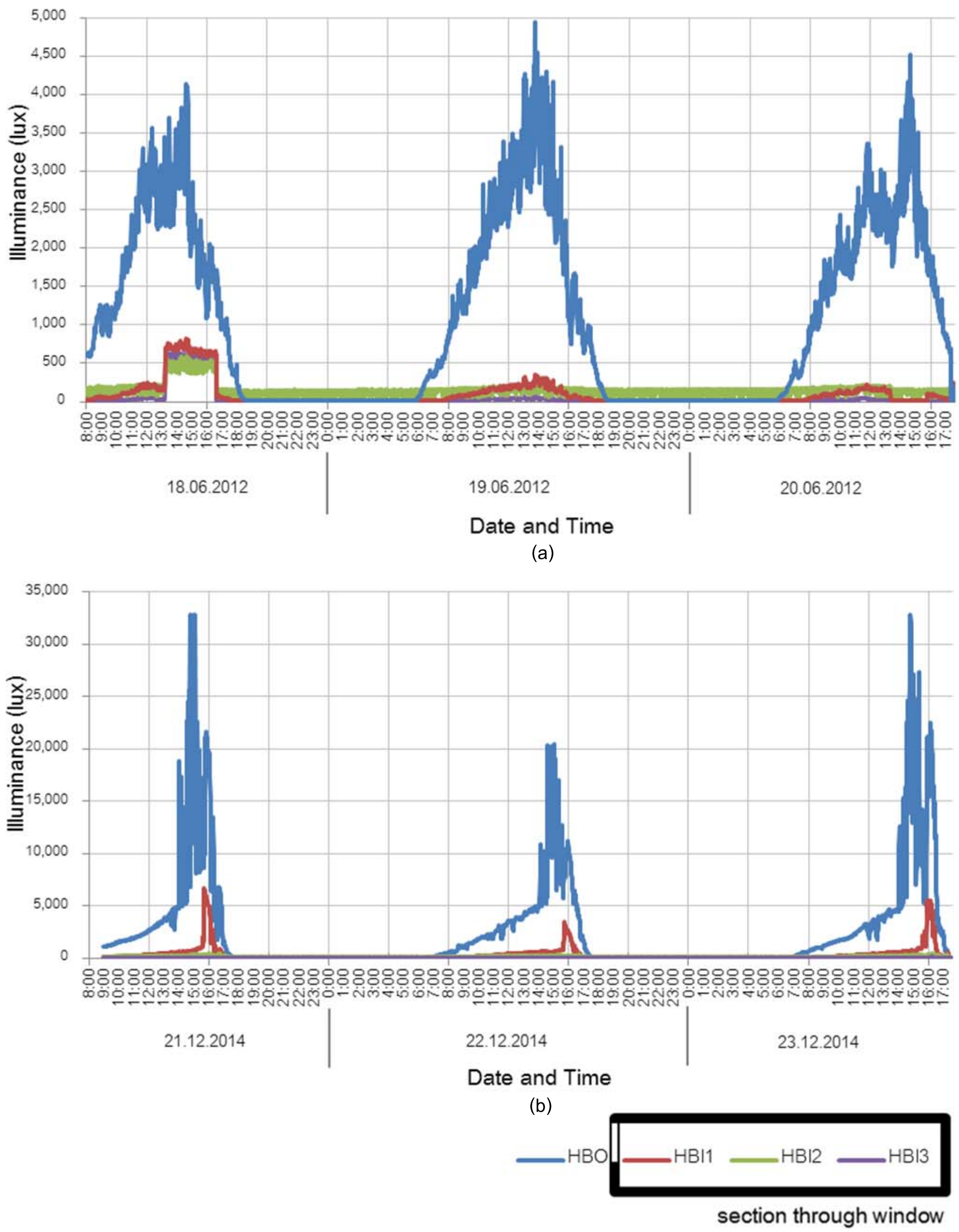


Fig.4. 24 Minutely illuminance of AR206 collected during: (a) 18th-20th June 2012 and (b) 21st-23rd December 2014.

Due to the impact of the sun, illumination data have the same pattern as temperature but are more extreme. Without natural light, the illuminance was zero during 6.30PM-6AM for summer and 7.30PM-7PM for winter (Figure 4.24). In contrast, illuminance fluctuated extremely in the day time. The maximum of ambient light level, for example, can be from 2,000 lux to more than 30,000 lux. When the sun rose up, illuminance increased from zero until it reached the peak at about 2-3PM and then reduced to zero again in the evening. The summer solstice data in Figure 4.24(a) shows that the highest illuminance were approximately 2,000-5,000 lux during 2-3PM. While the direct sun influenced the window in the winter, they were above 5,000 lux (see Figure 4.24(b)). When the summer and winter data were compared, it is obvious that the level of natural light rose gradually excepted when direct sun incident the logger sensor which usually happened during 2-4PM in winter.

The impact of direct sunlight in winter also influenced the HBI1 position at 4PM, resulting in the high intensity of the light at about 3,000-6,000 lux whereas it is about 200-1,000 lux in general. Room illuminance levels were normally limited. It is only the HBI1 position where illuminance possibly met the standard of 300 lux. As can be seen in Figure 4.24(a) and (b), illuminance of HBI1 was remarkably high in the afternoon compared to the other positions. It was substantially high for winter but for summer it hardly met the standard. For the occupied classrooms, afternoon classes on 18^{th} and 20^{th} June show in Figure 4.24(a) a distinct illumination pattern. For 18^{th} of June, illumination levels in all positions inside the room immediately increased to approximately 400-700 lux at 1PM and then decreased rapidly at 4.30PM. This is due to the fact that artificial lighting was fully switched on. Differently, illuminance at the HBI1 position dropped between 1PM and 4PM on 20^{th} of June. It resulted from the curtain being closed when the projector was used.

e. Carbon dioxide levels

The carbon dioxide rate was measured at the centre of the classroom in order to study the impact of occupants on classroom indoor air quality. All classrooms in the case study building were usually closed both when occupied and vacant. The CO2 of unused rooms was constant at approximately 500 ppm (Figure 4.25). It immediately rose significantly when the room was occupied on 18th and 20th June (Figure 4.25(a)). For 18th of June, the CO2 rate increased sharply from 1PM until reached the maximum at 1,200 ppm during 3-5PM. It then gradually reduced to meet 500 ppm again at 9PM on 19th June. On 20th June, it is the same pattern but with a much higher rate of more than 2,500 ppm. The difference between the two classes is the number of occupants, which is 9 persons for 18th June and 63 persons for 20th June.

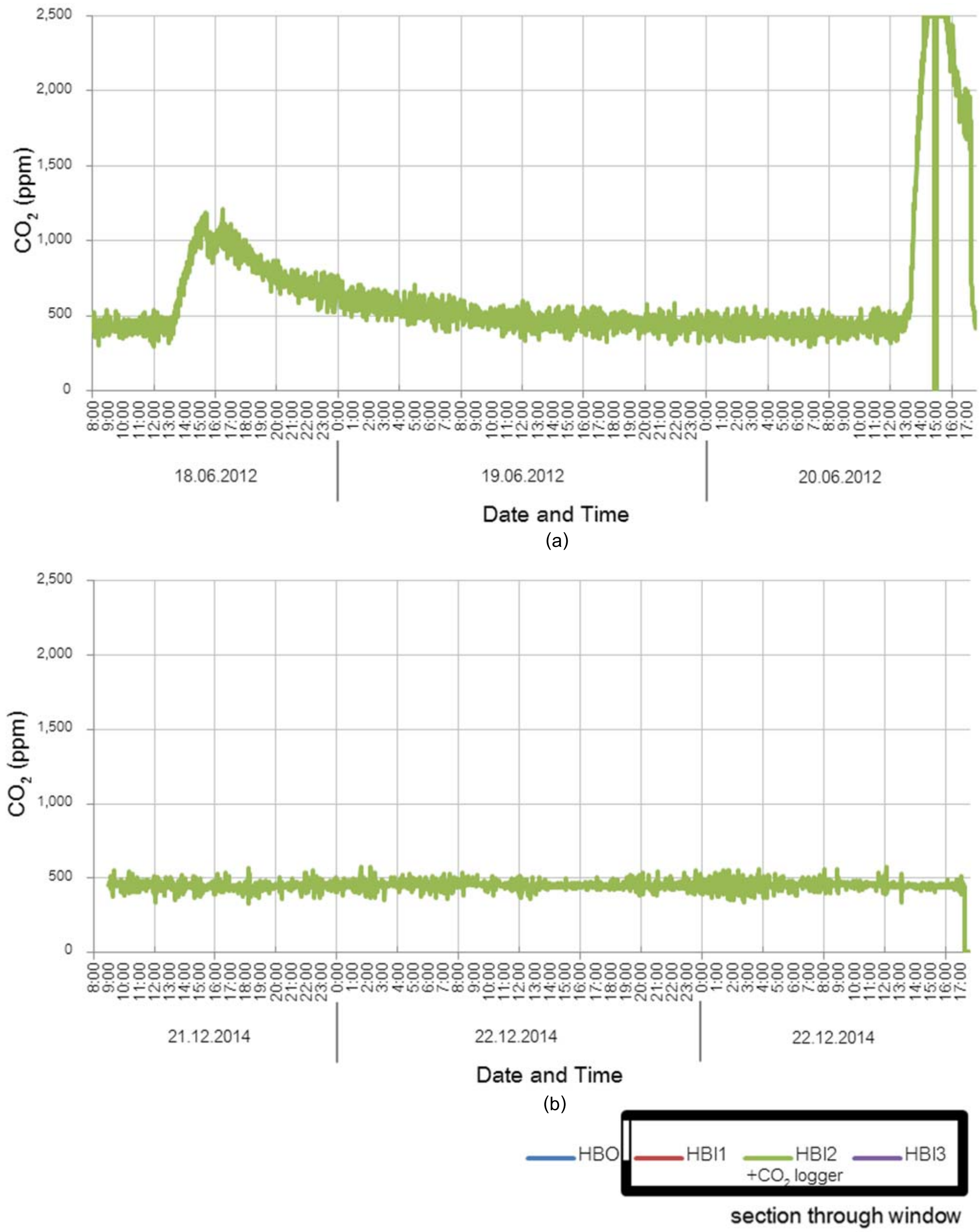


Fig.4. 25 Minute values of carbon dioxide levels for AR206, collected during: (a) 18th-20th June 2012 and (b) 21st-23rd December 2014.

2) Influence of existing façade on illuminance

There were three parameters of the existing façade and system that can affect visual comfort inside the classroom. They are window orientation, curtains and artificial light. Two classrooms were calibrated and simultaneously measured in order to compare those parameters to the base case. AR206 was selected to be base case in which the condition consisted of southwest orientation, opened curtain and off light. The results revealed the impact of each factor on illumination levels.

a. Window orientation

All classroom facades in the case study building faced to the southwest and the northwest. The classroom which were selected to represent these two window orientations were 60 seat classrooms located in the middle among other classrooms within the same corridor - AR206 for the southwest and AR313 for the northwest. The differences between these samples were their levels and surroundings. AR206 was on the first floor. With its own overhang, the window was also shaded by trees outside while the northwest classrooms on the second floor, including AR313, were not influenced by trees. However, the four-story high building nearby and large area of their adjacent terrace possibly affected on illumination levels of AR313.

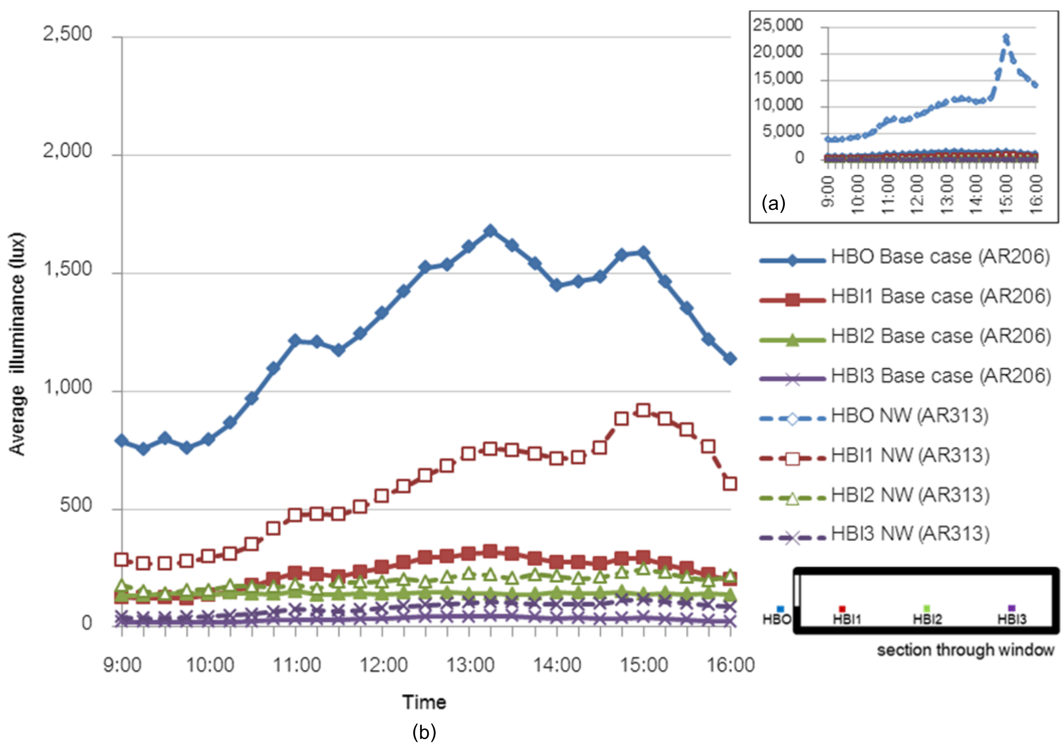


Fig.4. 26 Average illuminance of northwest orientation classroom compared to base case (southwest orientation) on 31st May 2012 (a) including and (b) excluding outdoor illuminance of northwest orientation.

When the illumination levels were compared, it was obvious that outside illuminance of AR313 which faced northwest was much higher than AR206 which represented a southwest orientation. In general, the illumination levels in the afternoon were considerably higher than in the morning for both orientations due to the impact of sun geometry which moved to the west during the afternoon. The graphs in Figure 4.26(a) show the impact of direct sun in the northwest orientation during summer that outdoor illuminance was much higher than that in southwest. The highest illuminance reached 24,000 lux at 3PM (see Figure 4.26(a)) while it was about 1,700 lux at 1PM and 3PM in base case (see Figure 4.26(b)).

The illumination levels of AR313 were higher than AR206 for all measured points because of the effect of direct sun. The considerably high light intensity of direct sun resulted in up to 600 lux higher illuminance than base case at HBI1. Expectedly, the difference of illuminance at HBI2 and HBI3 which located further from the window was much lower than HBI1. It resulted in no significant difference of illuminance between the two rooms.

When comparing to standards of 300-500 lux, HBI1 is the only position with the illuminance to meet the standard. The base case illuminance was close to the standard in the afternoon while it normally met the standard for AR313. Interestingly, direct sun appeared to have a positive effect on daylight quantity. However, this excessive high level of AR313 HBI1 might markedly contrast to the lowest illuminance at HBI3 when compared to AR206 which had less effect from direct sun.

b. Curtain

The measurement was obtained in AR205 and AR206, similar adjoining rooms, which had the translucent orange fabric curtain as the only internal shading device. Fully closed and opened conditions were assigned to AR205 and AR206 respectively. As long as the curtain was totally opened, the illumination levels of the area closed to the window were higher particularly in the afternoon when most of these levels met the requirement. Figure 4.27 shows that although outdoor illuminance of AR205 was slightly higher than base case, HBI1 illuminance was much lower as the curtain was closed. Illumination levels of HBI2 and HBI3 were very low and it was almost not different between two conditions.

A substantial low illuminance for HBI1 in AR205 reveals that the impact of curtain operation on using natural light was intense in the area nearby window. This result also implied that the translucent light from the curtain might be limited and have less impact on indoor brightness. However, application of curtain might be practical when using a computer.

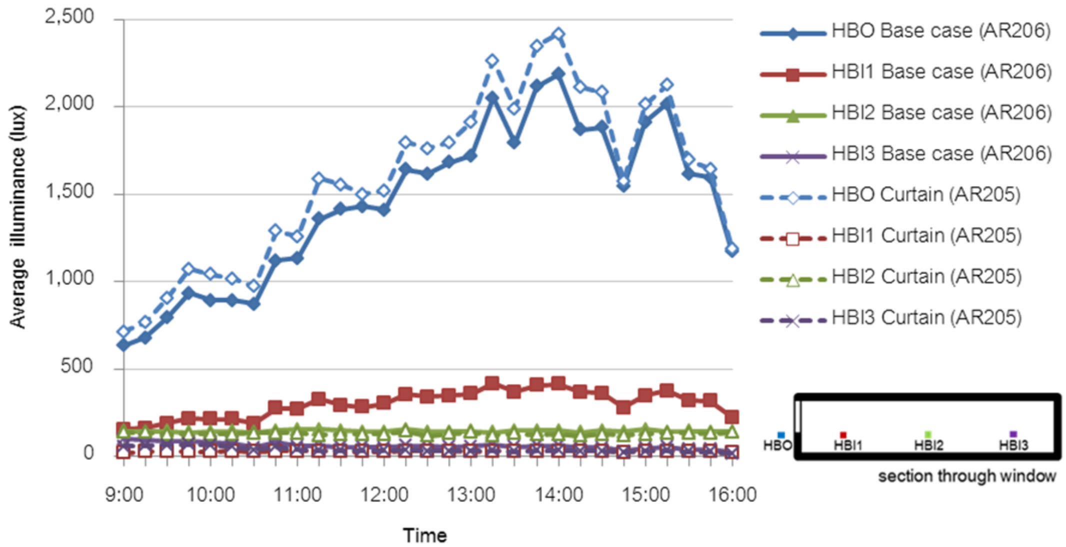


Fig.4. 27 Average illuminance of closed curtain condition compared to base case (opened curtain) on 5th June 2012.

c. Lighting

The two rooms were examined: AR206 for the natural light and AR205 for the combination of the daylight and the artificial light. As the experiment base case, AR206's brightness pattern was as common as the previous cases in that the greater the distance from the window, the less the illumination level. Commonly in summer, illuminance in the afternoon was higher than in the morning. It is illustrated in the graph in Figure 4.28 that there was no significant difference between two rooms excepted when artificial light was applied.

The utilisation of the light in AR205 between 9.00AM and 11.30AM can improve illumination level to meet the standard in every measured point. The illuminance of HBI1 was the highest. As shown in Figure 4.28, the lowest illuminance of AR205 was nearly 500 Lux at the HBI2 position which was in the middle of the room. The possible reasons could be this measured point was under the structural beam (the lighting layout has been provided in Figure 4.29). The beam located in the middle of two fluorescent lamps which were fixed at the ceiling above. It probably shaded some parts of the luminous flux leading to lower brightness levels. The actual effect of lighting is shown in the graphs of HBI3 (Figure 4.28). Whereas the HBI3 area appeared very dim in AR206, about 700 lux of illuminance was recorded when the lighting was integrated.

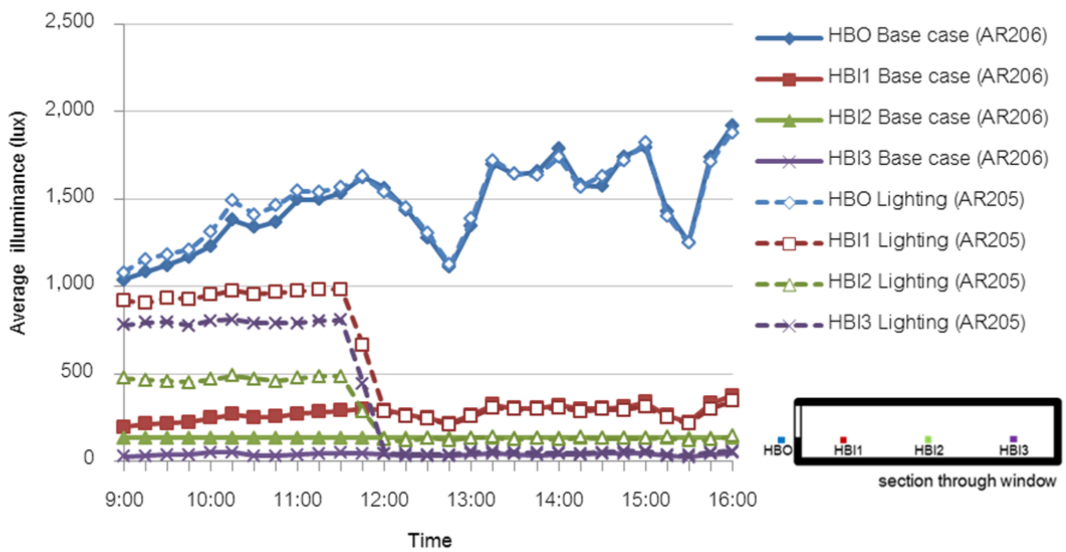


Fig.4. 28 Average illuminance of switched on light condition compared to base case (without lighting) on 16th June 2012.

Fig.4. 29 The lighting layout image of AR205 ceiling.

3) Daylight distribution

Because a 30 point distribution of daylighting conditions was measured one at a time using a Hagner lux meter, calibration was required in order to deal with daylight fluctuations. Figure 4.30 demonstrates a comparison of illuminance after calibrated to be equivalent device and time. In the middle row of the room, four HOBO loggers were placed outside at the position HBO and inside at HBI1, HBI2 and HBI3 respectively from the window to the opposite side of the room while Hagner was applied at the position 1, 2, 3, 4, 5 and 6 in row C. Minute outdoor illuminance was used to calibrate 30 point illuminance to be the same time. As shown in the graph, all of HOBO illumination levels were more than that from Hagner from about 15 to 300 lux. However, the illumination patterns of each condition were roughly similar. Four conditions of daylight distribution were studied: opened curtain and switched on light, closed curtain and switched on light, opened curtain and switched off light, and closed curtain and switched off light. Application of artificial light was included to examine the system impact. The distribution of daylight was interpreted by two indicators which are illuminance distribution and luminance ratio of 30 seating positions.

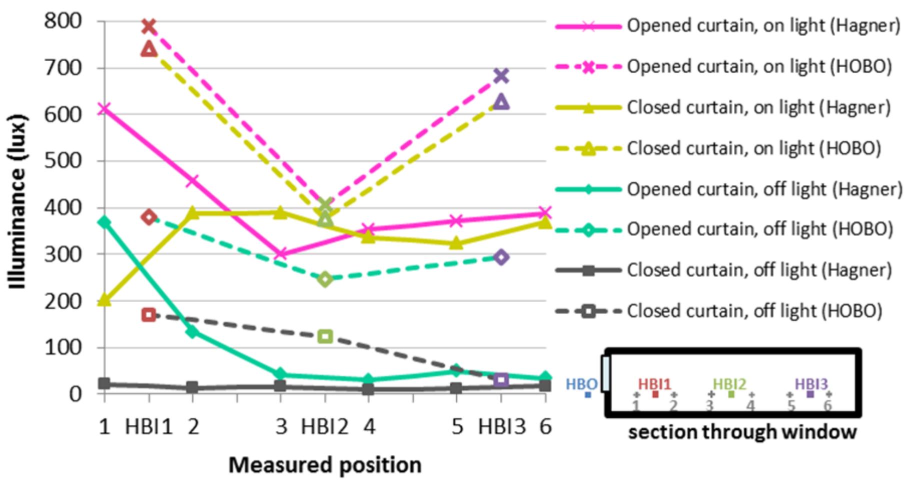


Fig.4. 30 Calibrated illuminance of Hagner lux meter and HOBO loggers.

The conditions considered consisted of opened and closed curtain, switched on and off lights during summer and winter times. Fully on (Figure 4.31(i)) and off (Figure 4.31(j)) artificial light were measured at night to study impact of lighting. For effects of lighting integration, two combinations of partly on lighting (Figure 4.31(k) and (l)) which was common conditions were selected. Apart from main light sources, the light from projector was the other source. It is obvious in Figure 4.31 that illuminance of off light conditions (Figure 4.31(c), (d), (g) and (h)) were lower than on light conditions (Figure 4.31(a), (b), (e) and (f)). Most of them was also lower than standard of 300 lux while the on light conditions generally met standard. The illuminance of partly switched on light conditions (Figure .4.31(k) and (l)) It can be seen in all charts that illuminance levels were low at furthest area from the window excepted when the light was turned on that the dimmest was in middle area of the room. The lighting case in Figure 4.31(i) can represent the actual effect of the light source on illuminance. The shade might be because of structural beams. The result analysis can be divided into four groups consisting of daylighting cases, fully lighting cases, partly lighting cases and dim environment cases.

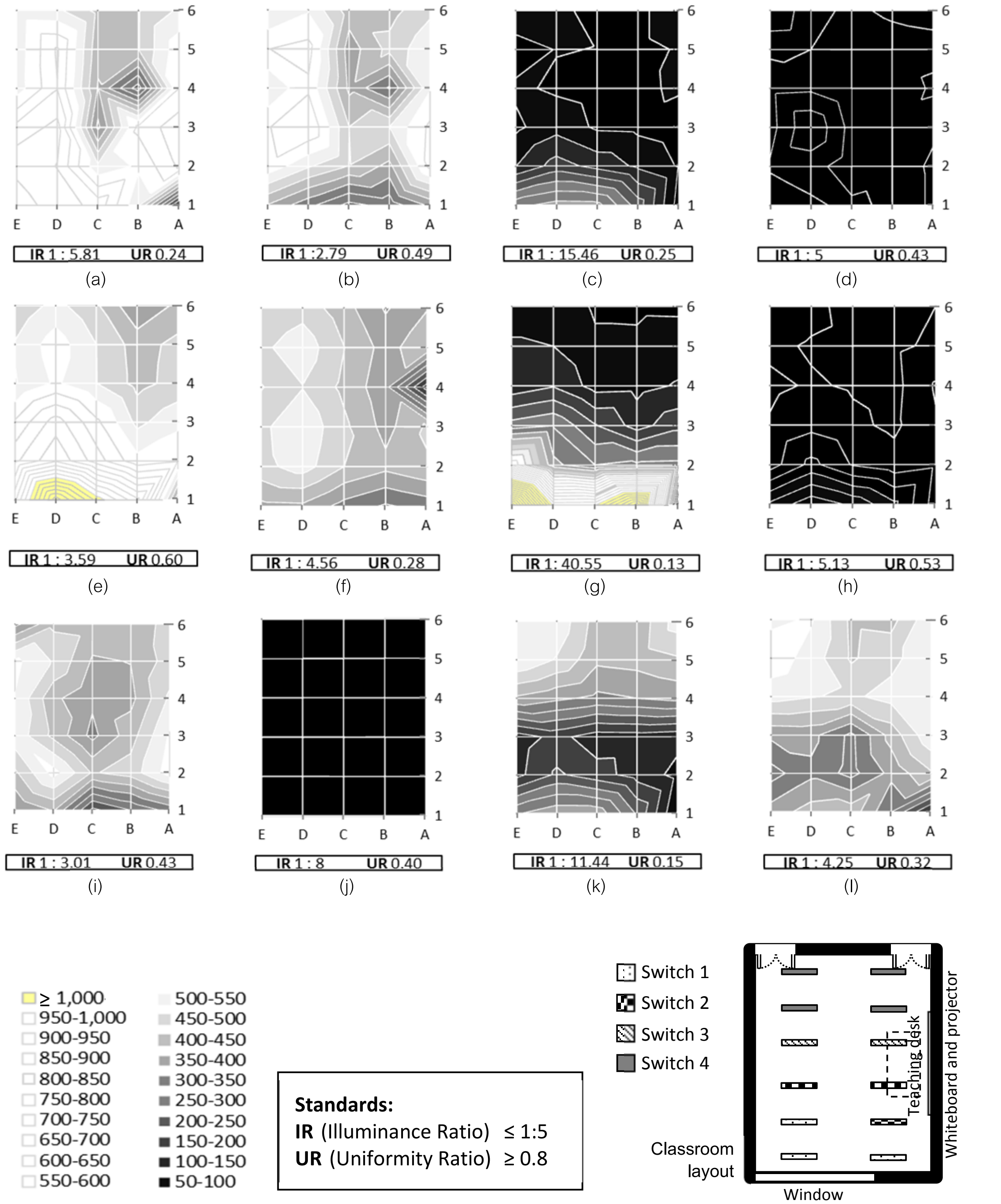


Fig.4. 31 Conditions of illuminance distribution: (a)-(d) on 9th Jun. 12, (e)-(h) on 10th-11st Jan. 15, (i)-(j) artificial light and (k)-(l) daylight and lighting combination on 9th Jun. 12; (a) and (e) opened curtain and switched on light, (b) and (f) closed curtain and switched on light, (c) and (g) opened curtain and switched off light, (d) and (h) closed curtain and switched off light, (i) switched on light, (j) switched off light, (k) on light switch 3 and 4, and (l) on light switch 2, 3 and 4.

When the curtain was opened the illuminance at places near the window became much higher than the other areas. It caused very high illuminance ratio and low uniformity ratio particularly in opened curtain and light off cases (Figure 4.31(c) and (g)). Illuminance ratios were 1:15.46 and 1:40.55 and uniformity ratio were 0.25 and 0.13 for summer and winter respectively. According to those data, winter distribution appeared worse than that in summer due to influence of direct sun, but it is not for all cases. For the lighting combination cases, illuminance ratio and uniformity ratio in winter (Figure 4.31(e)) were slightly better than those in summer (Figure 4.31(a)). The lowest illuminance was normally at A1 measured position located in the front of the room near the window. It is because the window area does not cover the teaching area in front of the room and so the area was generally shaded rather than bright.

Apart from sufficient illuminance provided, all full lighting cases (Figure 4.31(a), (b), (e), (f) and (i)) also brought about lower illuminance ratios than the daylighting cases. The combination of daylight and lighting in which direct sun was included in winter (shown in Figure 4.31(e)) was supposed to cause high illuminance ratios for the highest average illuminance. When compared to the summer case (Figure 4.31(a)) and closed curtain case (Figure 4.31(f)), it is a greater illuminance but with a rather lower illuminance ratio and higher uniformity ratio. This implies that the influence of direct sun in winter can improve minimum illuminance, resulting in desirable ratios.

As for the impact of only artificial light, the illuminance (Figure .4.31 (i)) was low in areas in the middle of the room and near the window. Theoretically, lighting which can be separately controlled parallel to the window is probably a practical solution. Partly applications of lighting to an opened curtain room in summer shown in Figure 4.31(k) and (l) might be able to present the solution. When the furthest artificial light from the window was applied, the more switches were turned on and the more areas met the illuminance standard. During the measurement period, utilization of two lighting sets caused inadequate illuminance in some parts (Figure 4.31(k)) until three light switches were applied (Figure 4.31(l)) when the majority of places met the illuminance standard. Moreover, illuminance ratio was lower than for the opened curtain case (Figure 4.31(c)). Although it possibly indicated more appropriate conditions, the results of uniformity ratio appear to disagree. The lower uniformity ratio might be because of too limited a minimum illuminance. Figure 4.31(l), for example, shows the average illuminance caused by preferable illumination levels in most areas of the room while it was just at A1 that illuminance was significant lower. If it is fully lighting cases (Figure 4.31(e)) which illuminance ratio was similar, the greater uniformity will arise from higher minimum illuminance despite the fact that the maximum illuminance was considerably high.

It can be concluded from the results that the more natural light influenced the room illuminance the worse illuminance contrast and uniformity ratio. It shows in Figure 4.31(c) and (g) that the illuminance ratios are much higher than standard of 1:5. However, it can be lessened by applying artificial light Figure 4.31(a) and (e). In terms of uniformity ratio, it is too low in all cases comparing to the standard of 0.8 although it was very little variation of illuminance such as in the dark room shown in Figure 4.31(j). The results imply that the recommendation might be too strict for this case.

For luminance, five to nine sighted vertical positions at 1.50 metre high were measured at 30 seating positions in summer and winter. Three conditions which are opened curtain and switched off light, opened curtain and closed off light, and fully switched on light were focused in order to examine impact of daylight, transparent light from curtain and artificial light respectively. Application of projector was also included in all cases. The results were shown in illuminance ratio of maximum and minimum luminance (Figure 4.32) and of projector and its background luminance (Figure 4.33-34).

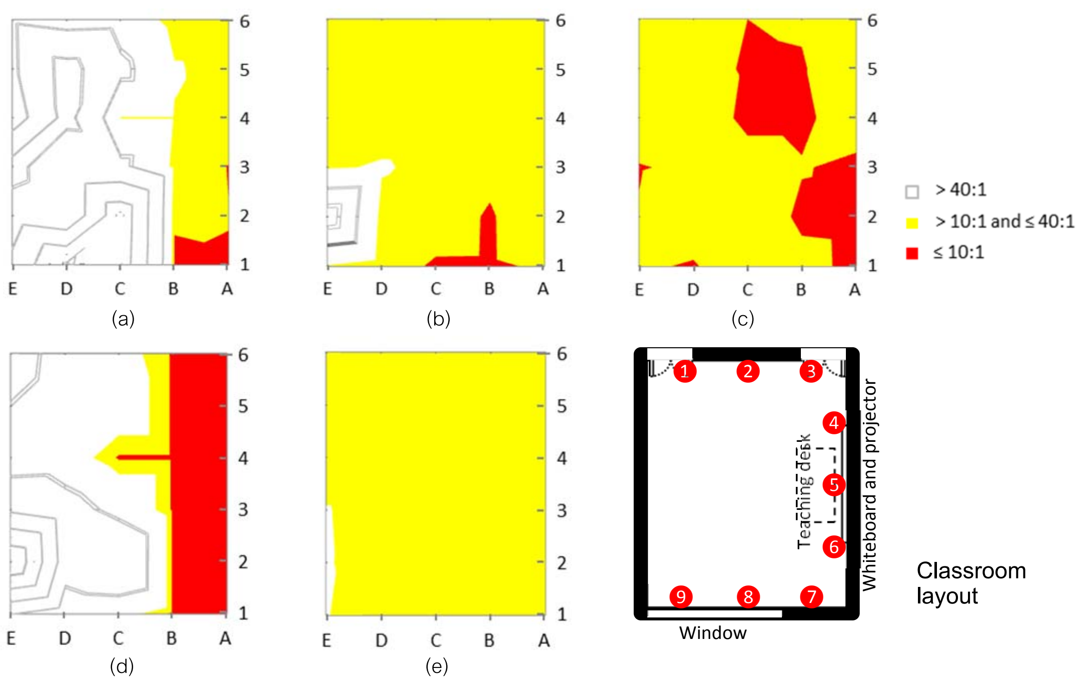


Fig.4. 32 Maximum and minimum luminance ratio of 30 measured points: (a) opened curtain and switched off light on 9th Jun. 12, (b) closed curtain and switched off light on 9th Jun. 12, (c) artificial light, (d) opened curtain and switched off light on 10th-11st Jan. 15, and (e) closed curtain and switched off light on 10th-11st Jan. 15.

In terms of vertical task and its surroundings, CIBSC (1994) suggested contrast in normal field of view that not more than 40:1. Charts in Figure 4.32 show that ratio totally met standard for lighting condition (Figure 4.32(c)). For the daylighting case which artificial light was not included (Figure 4.32(a) and (d)), variations of luminance were overwhelming in most of the area. Standardized ratios were only in the front area of the room. It appears that the ratios were acceptable in front of the room where either none or less of window area was in participants' field of view. Translucent light from the curtain itself brought about desirable ratios for almost all measured positions (see Figure 4.32(b) and (e)). A minority of ratios which did not meet the standard occurred near the window in the back of the room. Surprisingly, the ratios in winter (Figure 4.32(d) and(e)) were rather less than in summer (Figure 4.32(a) and (b)) on average despite the fact that direct sun influenced the area more. It is because not only the maximum luminance in winter was higher but the minimum was also higher than that in summer. The ratios in winter were rather lower in general.

The results reveal the impact of light source on vertical luminance depend on direction and pattern of illuminations. The top lighting of artificial light and low intensity diffused light which was transmitted from the curtain provided less contrast ratio of luminance than side lighting from unveiled window. In other words, the ratios can also be improved if light sources are either located outside the field of view or have a low intensity.

At visual tasks, ratios of projector screen luminance and luminance of its backgrounds aree presented in Fig.4.33-34. Separately, daylight, translucent light and artificial light were further studied. According to the recommendation of highest *ratio between luminaries and the surfaces adjacent to them* which is 20:1 (CIBSC, 1994), the ratio patterns of lighting case not only met the standard but were also the most consistent (Figure 4.33(c) and Figure 4.34(c)). When artificial light was excluded, comparative luminance ratios of the projector (LM2) and its background (LM1 and LM3) between daylighting case and translucent light case were different to the result of luminance in the field of view. The ratios of opened curtain cases (Figure 4.33(a), (d), Figure 4.34(a) and (d)) were generally lower than when the curtain was closed (Figure 4.33(b), (e), Figure 4.34(b) and (e)). All ratios of the former cases met the 20:1 criterion whereas there were some positions of translucent light cases in summer that ratios were more than the standard. It is because the high intensity of input light increased background luminance until approximated to the luminance of the projector screen. However, it cannot be concluded that less of variation is the better condition because the use of projector required dim environment. In addition, veiling reflection problem which was found in observation can probably be more serious for higher luminance.

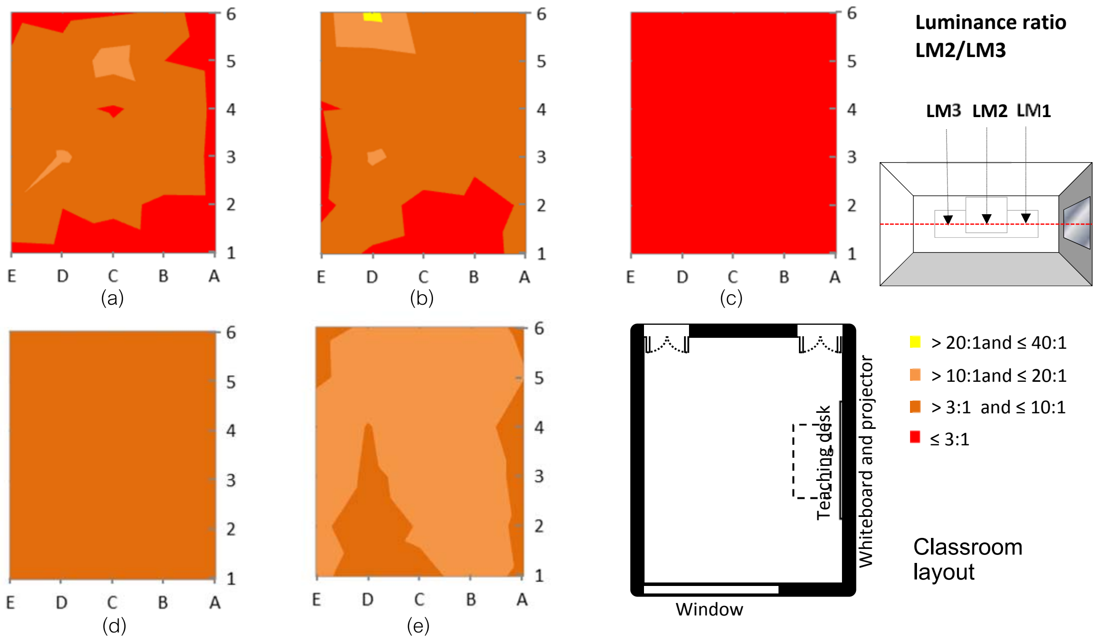


Fig.4. 33 Luminance ratio of projector screen (LM2) and its background (LM3) of 30 measured points.

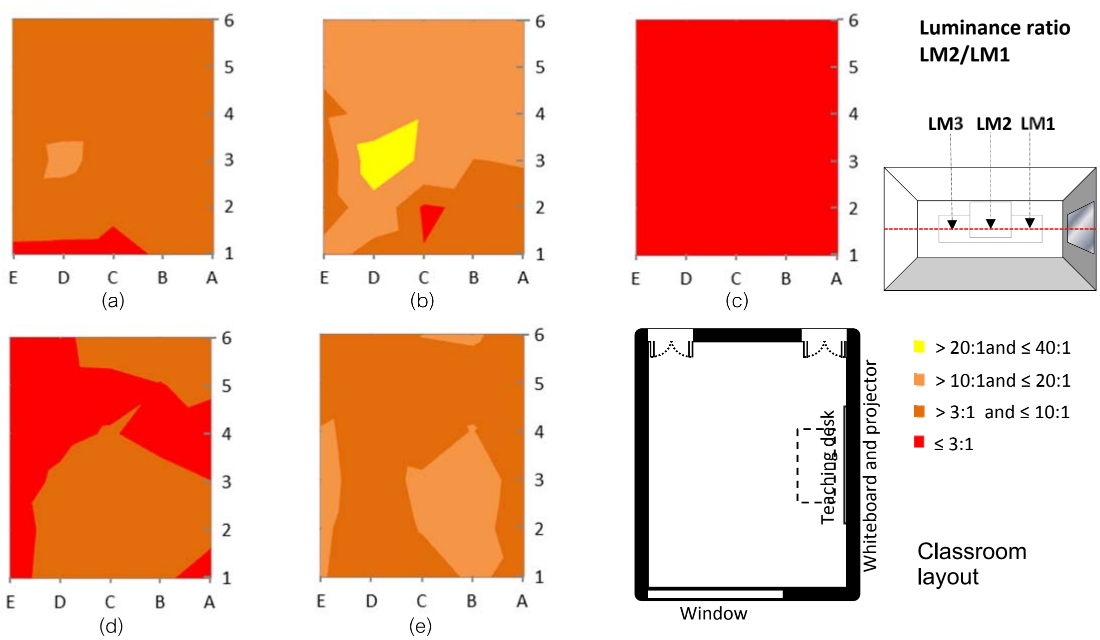


Fig.4. 34 Luminance ratio of projector screen (LM2) and its background (LM1) of 30 measured points. (a) opened curtain and switched off light (9th Jun. 12), (b) closed curtain and switched off light (9th Jun. 12), (c) artificial light, (d) opened curtain and switched off light (10th-11st Jan. 15), and (e) closed curtain and switched off light (10th-11st Jan. 15).

There are differences between ratios of projector screen to LM3 and LM1 which is the further and the nearer measured points of the window. Winter cases (Figure 4.33(d) and (e)) had less contrast than summer cases (Figure 4.33(a) and (b)) for ratios of LM3 while ratios of LM1 in winter was more than summer (Figure 4.34). Within summer, luminance ratios of LM3 (Figure 4.33(a) and (b)) were higher than of LM1 (Figure 4.34(a) and (b)). Differently, the LM1 ratios were higher for winter. The higher luminance of LM1 in winter reveals influence of direct sun light on vertical task near window area.

All in all, the natural light environment itself caused excessive high difference in maximum and minimum illuminance. The winter case appeared to have worse contrast than the summer case but it was better when the lighting was integrated. It reveals that natural light in summer was probably too limited in terms of amount and distribution. The daylighting case also brought about high luminance contrast in most areas of the room. The winter ratios were more satisfactory than for the summer. The contrast of projector screen to its background mostly agreed with the recommendation but there were more factors, such as quality of projector and reflection from the whiteboard, that might influence visual comfort.

4.4 Standard verification

According to previous research, Ramasoot and Fotios (2009) for example, some recommendations were considered to be impractical and out of date, especially for tropical climates, daylighting environment or spaces using display screen equipment. In order to verify the standards a classroom was examined. Participants were assigned to sit at 30 positions. At the same time as measurements, they were questioned about their brightness sensation. Studied indicators consisted of illuminance on student lecture desks, differences between maximum and minimum illuminance, and luminance at vertical tasks.

1) Illuminance of horizontal working plane

The present recommendation for classroom illuminance is between 300-500 lux (Loe et al., 1999). The standard has been used to assess minimum requirement that may not be able to specify visual comfort as excessive high illuminance can cause glare. Various ratios were raised to indicate appropriated variation of illuminance. Two simple ratios, uniformity ratio and illuminance ratio, were selected for this research that uncomplicated measurements were obtained. Suggested uniformity ratio is at least 0.8 (Loe et al., 1999) while variation of *general background to task* and of *minimum to maximum illuminance* are required to be not more than 1:5 (da Silva et al., 2012 and Alrubaih et al., 2013).

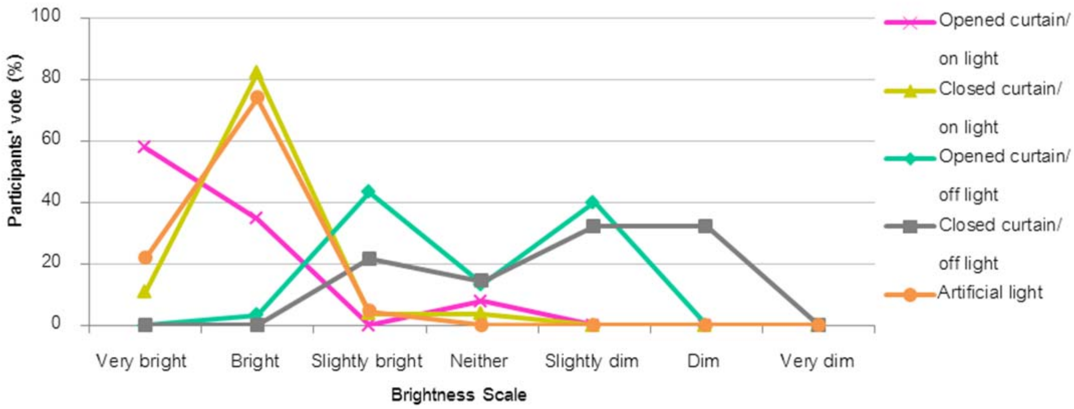


Fig.4. 35 Participants' vote on the room brightness for five lighting conditions.

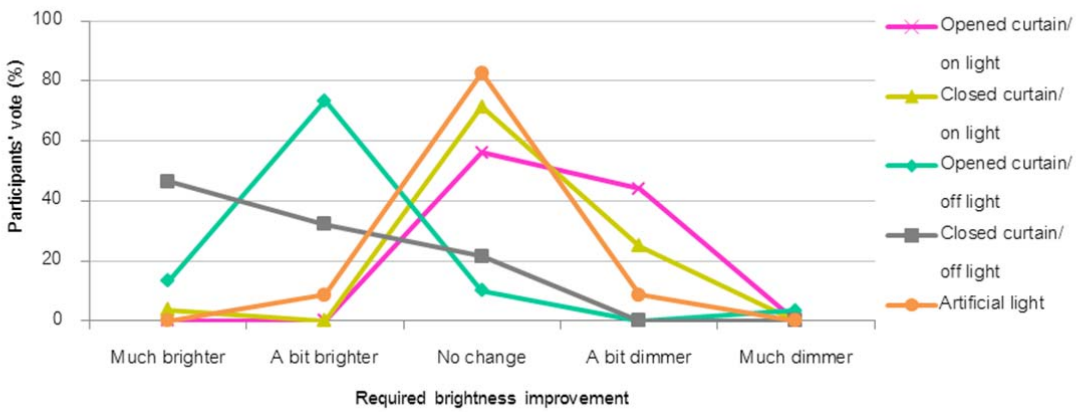


Fig.4. 36 Participants' requirement for brightness improvement for five lighting conditions.

Five brightness conditions consisting of opened curtain and switched on light, closed curtain and switched on light, opened curtain and switched off light, closed curtain and switched off light, and artificial light (Figure 4.35-36). As expectedly, the artificial light condition satisfied the participants due to majority of them voting that it is was *bright* and they need *no change* for this brightness condition. The brightness appearance of four conditions which natural light influence are illustrated in Figure 4.37. Obviously, when lighting was applied the room was bright whether the curtain was opened or not. The closed curtain appears to be the more satisfied condition than the opened curtain case as most of participants required *no change* for this condition. They felt that it was *bright*. For the opened curtain condition, although parts of them agreed to the brightness, there were another significant comment raised that the room was required to be *a bit dimmer* while they specified that it was either *very bright* or *bright*. When lighting was not included, the brightness appears less satisfied. The participants voted approximately half for *slightly bright* and half *slightly dim* for opened curtain and switched off light condition, resulting from significant differences in brightness condition between the near window and opposite side areas. *A bit brighter* was their preferred condition for this case. According to Figure 4.35, the closed curtain and switched off light was the dimmest condition. The brightness was indicated as *dim* environment that *much brighter* condition was required.

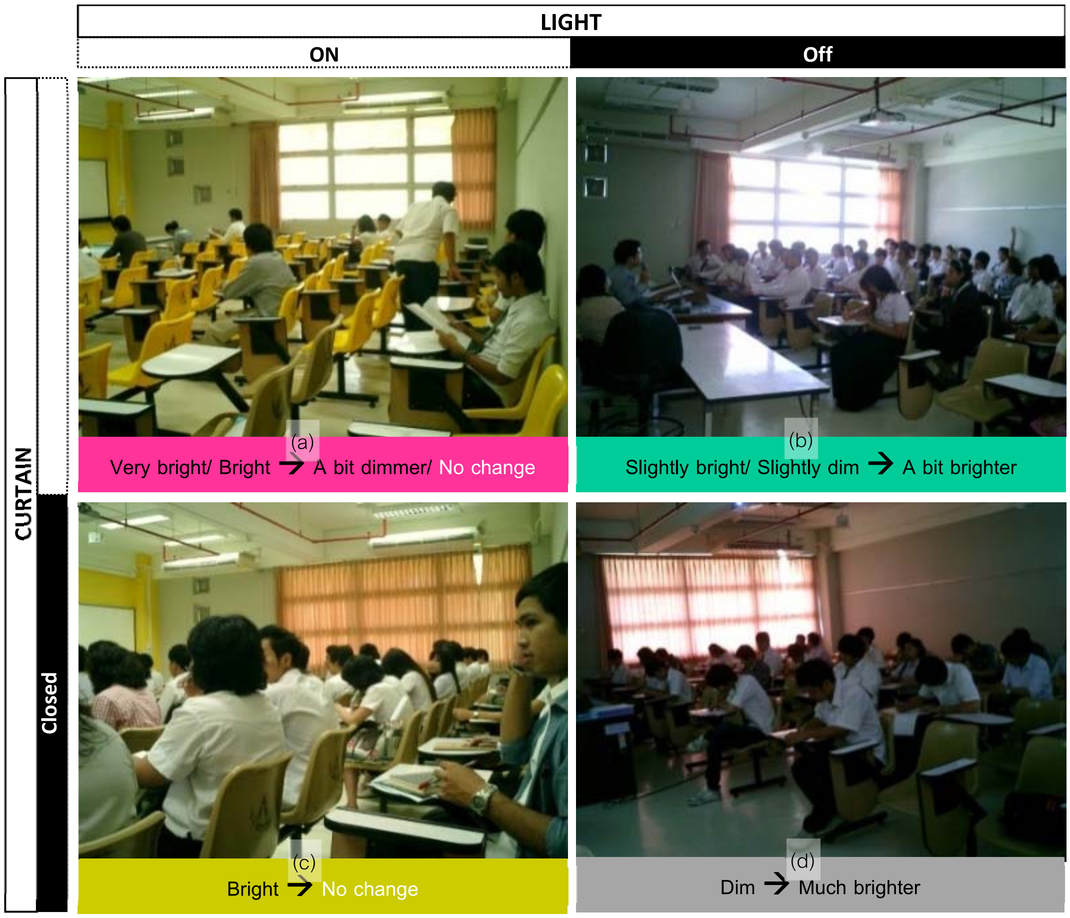


Fig.4. 37 Images of four of the brightness control systems conditions with occupants' comments of brightness sensation and requirements for each case: (a) opened curtain and switched on light, (b) opened curtain and switched off light, (c) closed curtain and switched on light, and (d) closed curtain and switched off light.

Figure 4.38 shows the relationship between participants' brightness sensation and illuminance which was collect at the exact time of the survey. The ranges were combined with the measured results in Figure 4.39. The applications of artificial light were found to improve brightness conditions to meet the lighting standard. When the light was excluded, the majority of illuminance was much lower than the standard. However, the standard range was generally indicated to be *bright* and *very bright* condition. Due to the fact that *bright* condition did not need to be improved, the condition probably is the most preferred condition. The *very bright* condition which occurred in opened curtain and switched on light possibly cannot satisfy the users in general. The conditions from *slightly dim* to *slightly bright* are in the range from 23 to 320 lux. These conditions supposed to be the most satisfies condition but a bit more brightness was required. However, the fact that neutral levels are totally lower than standard imply that the condition might be acceptable.

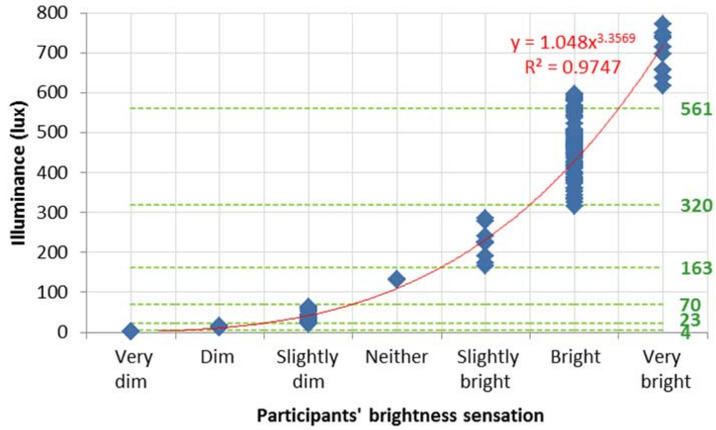


Fig.4. 38 Relationship between illuminance and participants' sensation of the room brightness.

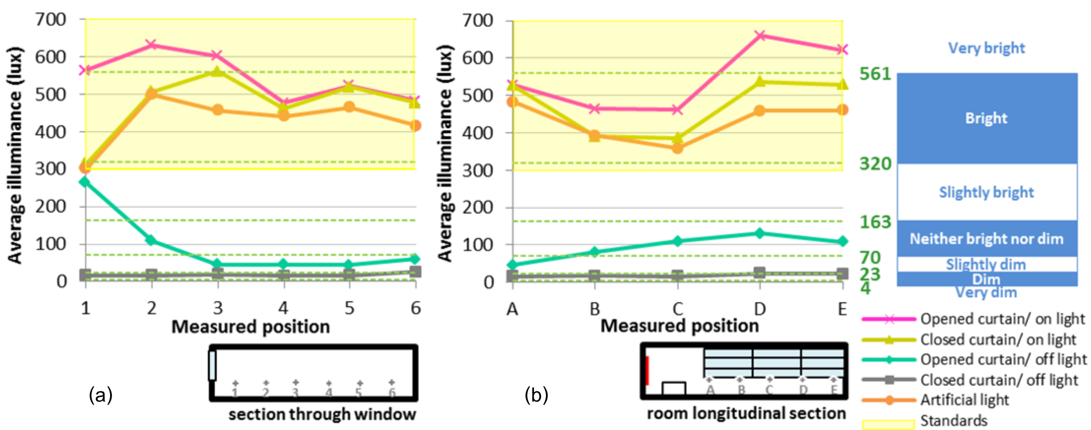


Fig.4. 39 Average illuminance of five brightness conditions: (a) through window and (b) longitudinal section of the room.

In terms of illuminance variation, the uniformity ratios which were illustrated in Figure 4.31 specify no condition where that the ratios meet the recommendation. It might indicate that all brightness conditions were discomfort while participants' opinions shown in Figure 4.40 appear not agree. Whereas the ratios are much lower than 0.80, there are three conditions that majority of participants voted to be *comfort* for using lecture desk. In addition, uniform illuminance was definitely recommended but the more uniformity ratio does not guarantee to be the more comfort condition. Containing high uniformity ratio comparing to other cases, the closed curtain and switched off light case rather was generally rated to be discomfort condition. It reveals that uniformity of illuminance might be able to indicate visual comfort except when illumination levels were commonly limited. In terms of contrast ratio, closed curtain and switched on light and artificial light conditions not only provided minimum contrast but also were mostly ranked to be comfort condition. As brightest and dimmest conditions, opened curtain and switched on light and closed curtain and switched off light conditions are supposed to be different. The results were rather approximate despite the fact that participants' sensation was separate: *comfort* for the brighter and *discomfort* for the dimmer condition. Moreover, about half of participants rated *comfort* for the natural light condition in spite of its contrast ratio was excessive high. The results reveal usefulness of the ratio only for bright conditions. Overwhelmingly, the ratio indicated that significant differences of illuminance and limited area of bright environment probably caused visual discomfort for the majority of users.

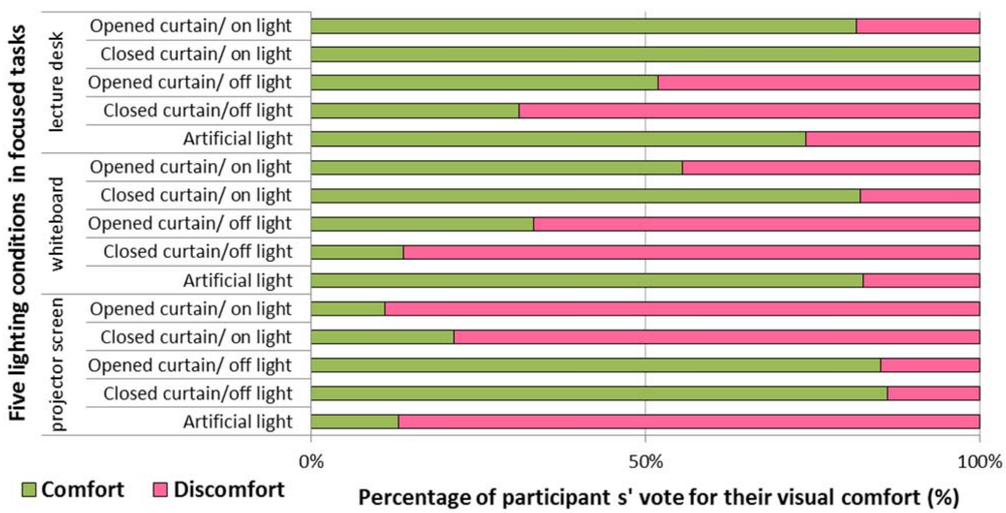


Fig.4. 40 Votes of visual comfort on three focused tasks in five lighting conditions.

It can be concluded that the most satisfied range probably is between 320-561 lux, which is within standard. The upper and lower cases might not be the users' preference but possibly are acceptable. Recommendations for uniformity ratio were confirmed to be too strict while the brightness contrast ratio is more realistic. Both ratios might not be practical for dim environments.

2) Vertical luminance

Some evidences (eg. Love, 1990 and Altomonte, 2009) suggested that it was not horizontal illuminance but vertical luminance that can indicate visual comfort. For general seeing and use of projector and whiteboard, two ratios were examined: a 40:1 overall luminance in field of view and 20:1 for the projector and the whiteboard which is also the surface adjacent to the projector.

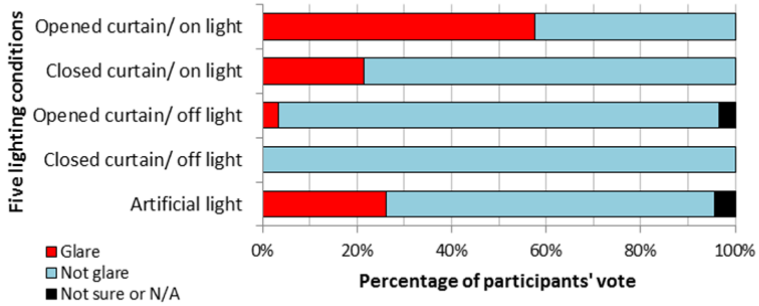


Fig.4. 41 Participants' vote about glare for five lighting conditions.

According to Figure 4.32, luminance ratios were lower than the limit of 40:1 for all positions in the lighting condition. The result agreed with participants' votes in Figure 4.36 that most of users preferred no change for this condition. In addition, only a minority of participants vote glare for the artificial light condition (see Figure 4.41). According to observation, the problem probably results from excessive high luminance and veiling reflection on the whiteboard. For the case of the natural light environment, the participants' sensation and application of ratio standard are in agreement. For three-quarters of the room that ratio were higher than recommendation (Figure 4.32) while most participants preferred brighter condition (Figure 4.36) and voted the condition *not glare* (Figure 4.41). It reveals that excessive high luminance ratio can indicate drawback of too much variation. The differences of maximum luminance from window and minimum luminance from the opposite side might not be able to indicate glare. It is probably because side lighting which normally located at the far field of view has less impact on eye sensitivity or the luminance from window. As the dimmest condition, the closed curtain case cannot satisfy the users due to insufficient brightness (Figure 4.35-36) whereas luminance ratios in most area of the room met standard (Figure 4.32). Although overwhelming ratio was confirm can be indicated visual discomfort, the results repeatedly point out impractical of luminance ratio for inadequate lighting condition.

In terms of task luminance, luminance ratios appear to meet standard for all cases except some positions with closed curtain and switched off light condition (see Figure 4.33-34). It agrees with votes of comfort in Figure 4.40. Most of the participants voted *comfort* for brightness of the whiteboard in the natural light environment and artificial light condition but *discomfort* for the translucent case (Figure 4.40). Differently, the comfort of seeing projector probably does not depend on contrast of luminance. The dim environment such as the two switched off light cases brought about considerable high proportion for *comfort* votes (shown in Figure 4.40). Containing the lowest luminance ratio, the lighting condition rather caused *discomfort* in general. Apart from the dim environment needs, the quality of the projector also can be one of the key reasons for the discomfort condition. The need for a dim environment is actually due to the low contrast of the existing equipment. In other words, the problem can be solved by improving the equipment to a high contrast projector.

Consequently, the almost all of the standards are still practical when comparing to participants' sensations. Uniformity ratio is excluded because it is too strict. However, the standard might be applied with two exceptions. Firstly, the illuminance levels which were not much lower than standards also can be counted as acceptable level. Secondly, all contrast ratios might not be realistic for less brightness environments.

4.5 Representation of the case study

In order to generalise the result of this study, representation case studies can be examined. The Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University was selected to be the main case study in this study. Additional case studies were also surveyed in the same method for confirming representation of the main case study. All additional case studies selected were university lecture rooms which contained approximately 60 seats and similar teaching devices.

1) The additional case studies

The main criterion of the additional case study selection was the university lecture rooms to approximate to the main case study in terms of capacity. According to the preliminary survey, the 60 seat classroom is one of the most popular classroom sizes in most faculties and can be found as medium size classrooms in shared classrooms in some compact universities. For the location, four regions of Thailand were focused as the country representatives. The regions: the south, the central, the northeast and the north approximately located on the latitude of 8°N, 14°N, 16°N and 18°N respectively. The building owner permissions and some specific difficulties are other issues of the selection. Eight buildings from all regions were surveyed but only four buildings that complete information were collected. The additional case studies consist of room SNP3 of Arch KKU, room 1712 of SC SWU, room 5111 SC CRRU and room 5406A PSU. They are lecture rooms that contain 50-70 seats and the same type of teaching devices. The building system consisted of lighting and air conditioning systems are also similar. Three of them were generally occupied by faculty students, two for Science and one for Architecture while the rest was shared to all faculties in the university. In order to calibrate the result from the survey, data collection of the room AR207 of the main case study was obtained as the survey base case at the same time as each survey. All data collected from the surveys was concluded in Appendix B while the general information of the case studies is shown in the Table 4.3.

Tab.4. 3 General information of the case studies

	The main base case	The additional case study			
Owner	ARCH MSU	ARCH KKU	SC SWU	SC CRRU	PSU
Room	AR207	SNP 3	1712	5111	5406 A
Latitude	16.43N	16.47N	13.75N	19.99N	7.89N
Longtitude	102.83E	102.83E	100.57E	99.85E	99.35E
Region	Northeast	Northeast	Central	North	South
Window orientation (CW degree from normal axis)	Southwest (9°)	Northwest (2°)	East	North (5°)	Northwest (19°)
Height (m.) of room floor from ground	5.3	10.1	65	0.7	14
Distance (m.) from main window to the nearest surrounding at the same height	66	2.5	no surroundings	20	no surroundings

a. Room SNP3 of Arch KKU

The SNP3 located on the second floor of the SNP building, Faculty of Architecture, Khon Kaen University, Khon Kaen in the northeast of Thailand. Classrooms in this building have been used as additional classrooms when spaces in the main building become inadequate due to faculty expansion. Because they are the same faculty, the use of the room and users' behaviour were very similar to the main case study. However, the room is in a specific shape i.e. the room width is smaller than the room length. Apart from the main window, the room also contains view windows in the corridor side which opposite to the main window and top window at the back of the room. Appearance of the case study was provided in Appendix B.

b. Room 1712 of Sc SWU

Room 1712 is one of the classrooms in building number 19 of Faculty of Sciences, Srinakharinwirot University, Bangkok in the central of Thailand. The room is located in the 16th floor where the students majoring in Jewelry, Department of General Science, are generally occupied. The operated time regularly starts earlier and finishes late than the main case study for an hour. The room has very specific elements such as washing basin next to the main window because the purpose of the room was changed from the original design which is laboratory. However, it has been used for lecture purpose only since it was built because there are specific spaces such as laboratories and conference rooms provided in other purposes. Other distinct features consist of the fully glazed wall at the back of the room and the excessive width of the room. It is because the room was divided from large laboratory. As it is tall building, the room corridor is single loaded and glazing closed and the outside spaces are limited. The building appears lack of well planning for placing condensing units of air conditioning system. Condensing units were placed outside the room in the positions that obstruct the main window from outside view. More details can be found in Appendix B.

c. Room 5111 of Sc CRRU

Room 5111 is a room in the Maths Building belonging to the Faculty of Sciences and Technology, Chiang Rai Rajabhat University, Chiangrai in the north of Thailand. The operated time and users' behavior are similar to the room 1712 of Sc SWU as the main users are also science students and staffs who major in Maths. The building is two story high, containing typical classrooms on the ground floor and a large lecture theatre on the first floor. Located on the ground floor, the room corridor appears to be pass way to the main faculty building. The room is the smallest classroom comparing to the other case studies. Apart from room size, tint glazing and two opposite side windows aree specific features of the room. Additionally, the room is the only case that generally uses electrical fans as the cooling devices. Details were already provided in Appendix B.

d. Room 5406A of PSU

The Prince of Songkla University Phuket Campus is in Phuket in the south of Thailand. It is a compact university campus that most faculties basically share learning spaces. There are three buildings that majorly contain share lecture rooms. Room 5406A is one of medium size classrooms located on the 3rd floor in the Academic Service Center Building. Because it is for sharing, the room is regularly occupied more frequent, earlier and late than the main case study. The classroom corridor is double loaded which can rarely be found in Thailand. Similar to the room 5111 of Sc CRRU, it contains two opposite side windows using tint glazing. Another different feature is the main window side consisted of small separate window placed in the middle of column spans.

2) Differences of weather data

Located in different position, the five case studies obviously cannot be directly compared because not only are the sizes of the rooms and window orientations different, but the weather and sun geometry are also different. In order to calibrate problem monitoring in different regions, weather data of each additional cases were measured at the same time as the case study using the same devices as the previous surveys, but the measure points were reduced to be outside and mid room positions. The measurement of each additional case was obtained separately during March – May 2016.

Figure 4.42 – 4.45 show weather data of SNP3 of Arch KKU, 1712 of Sc SWU, 5111 of Sc CRRU and 5406A of PSU comparing to the base case: AR 207 of Arch MSU. The focused data are temperature, RH, illuminance and CO_2 rate. The rooms were set opened curtain, closed window, switched off lighting and AC at the beginning as the base case. The data were obtained in both conditions: occupied and unoccupied in

most case except the case SNP3 of Arch KKU where the room was not allowed to be measured at the time it was occupied.

For SNP3, the data were collected during May 2016. The data contain both similar and different patterns when compare to the base case. The similar patterns occur on 19th while the differences were found on 18th.

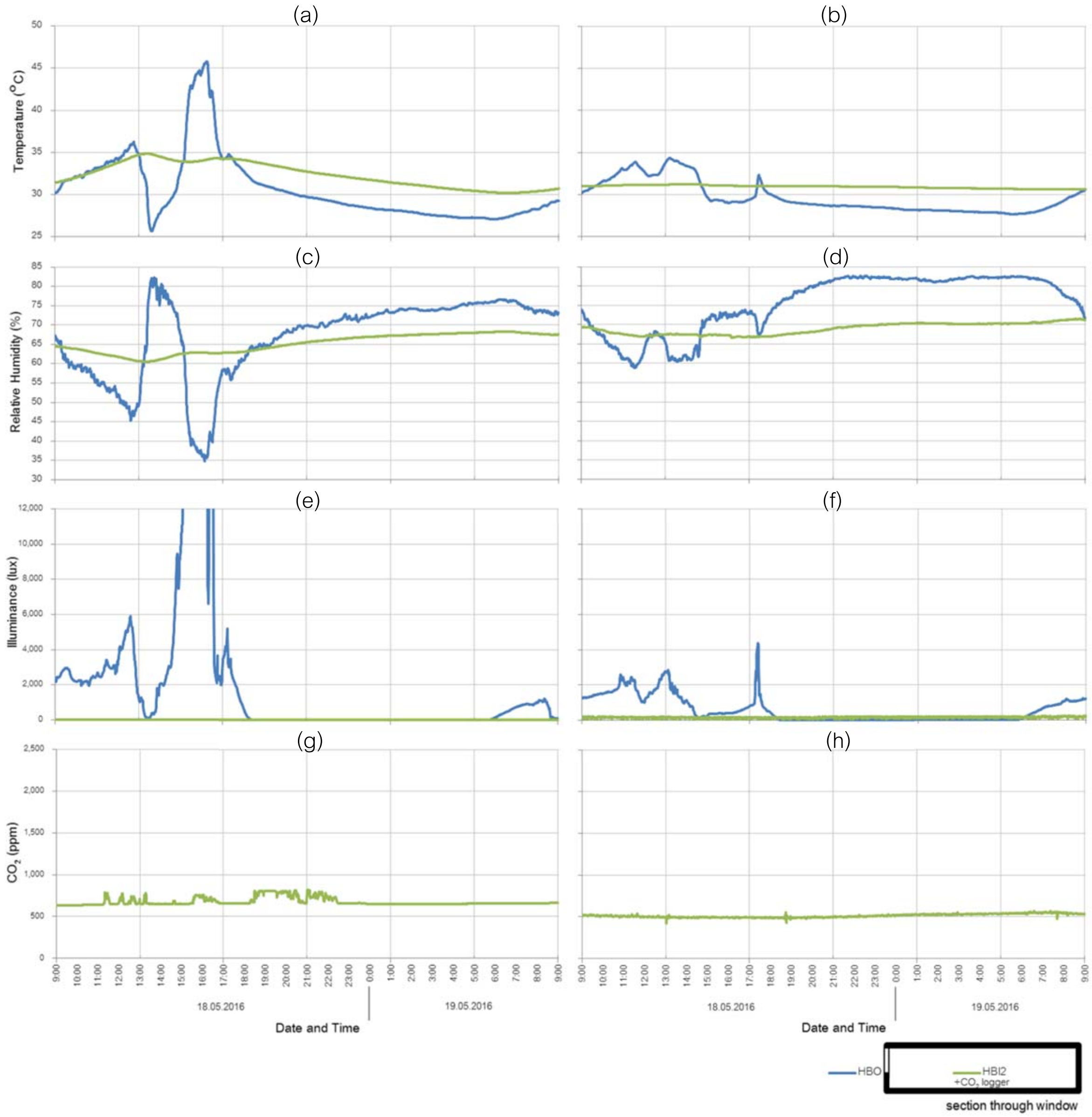


Fig.4. 42 Comparison of measured weather data of SNP3 of Arch KKU to the main base case: (a) temperature of SNP3, (b) temperature of AR207, (c) RH of SNP3, (d) RH of AR207, (e) illuminance of SNP3, (f) illuminance of AR207, (g) CO_2 of SNP3 and (h) CO_2 of AR207

In the case of Thailand weather, June is in the rainy season that is influenced by the southwest monsoon. In the measured dates. RH was generally high when different measured dates of the base case were compared. Because they located close to each other in the northeast of Thailand, similarity of weather data is expected. Obviously, the differences were found because of effect of direct sun shown in Figure 4.42 (e). Effect of direct sun causes high level of illumination and temperature while the RH was reduced. It reveals that the weather data in the same area can be different due to some incident effects such as fluctuation of could cover.

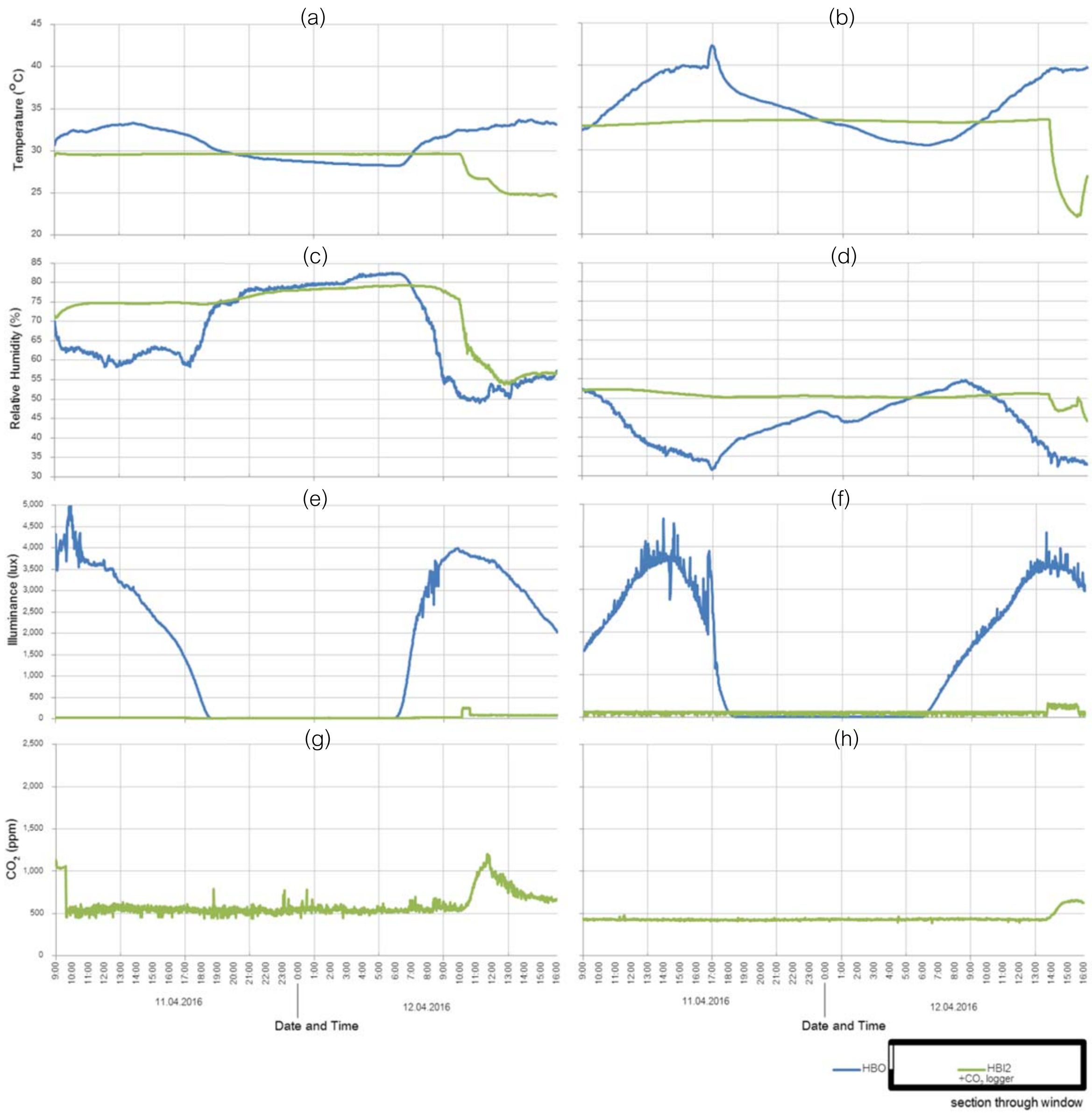


Fig.4. 43 Comparison of measured weather data of 1712 of Sc SWU to the main base case: (a) temperature of 1712, (b) temperature of AR207, (c) RH of 1712, (d) RH of AR207, (e) illuminance of 1712, (f) illuminance of AR207, (g) CO_2 of 1712 and (h) CO_2 of AR207

According to review of Bangkok and Mahasarakham weather data in chapter 2, temperature and RH of the room 1712 supposed to be higher than the base case. Without influence of monsoon, outdoor RH on 11st - 12nd of April is similar to the review while outdoor temperature of the base case became higher. The internal weather data are lower and more constant but consistent with the outdoor patterns. Levels of illumination are in the same pattern both for outdoor and indoor including the illuminance of artificial light shown in Figure 4.43 (e) and (f) which increased for about 300 lux when the rooms were occupied.

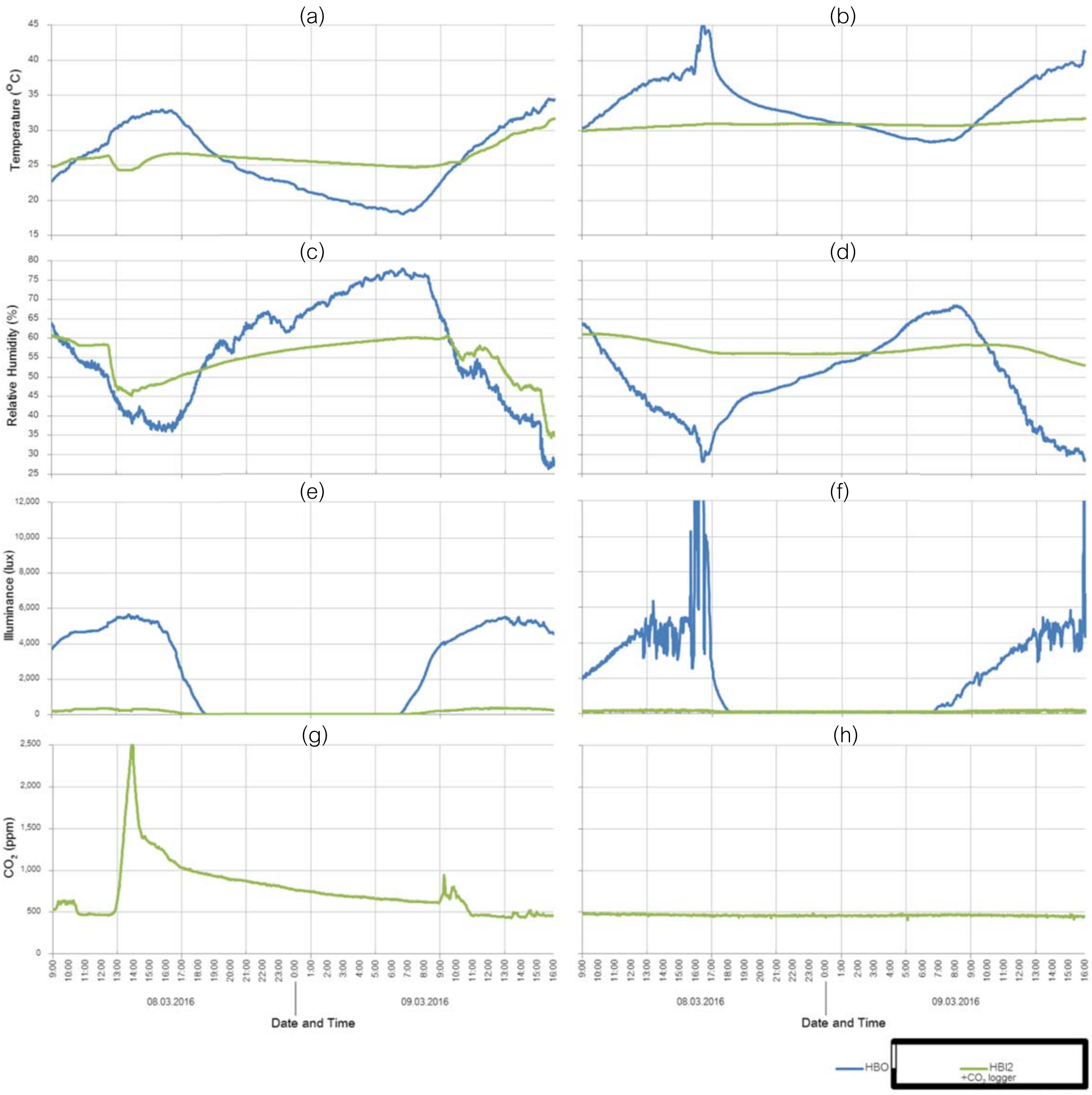


Fig.4. 44 Comparison of measured weather data of 5111 of Sc CRRU to the main base case: (a) temperature of 5111, (b) temperature of AR207, (c) RH of 5111, (d) RH of AR207, (e) illuminance of 5111, (f) illuminance of AR207, (g) CO_2 of 5111 and (h) CO_2 of AR207

Temperature and RH of 5111 which located in the north supposed to be lower than the base case, but the results are partly different: the RH is slightly higher. Except the time that the room 5111 was occupied in the morning of 8th March, weather data of the two cases has similar pattern in general. Significant results of illumination can be outdoor illuminance of 5111 approximates to the base case in most time when direct sun of the base case data was excluded. When the direct sun was considered, the indoor illuminance of AR207 supposed to be higher but the room 5111 contain more internal illuminance. The result implies advantages of some specific features of the room 5111 that should be further studied.

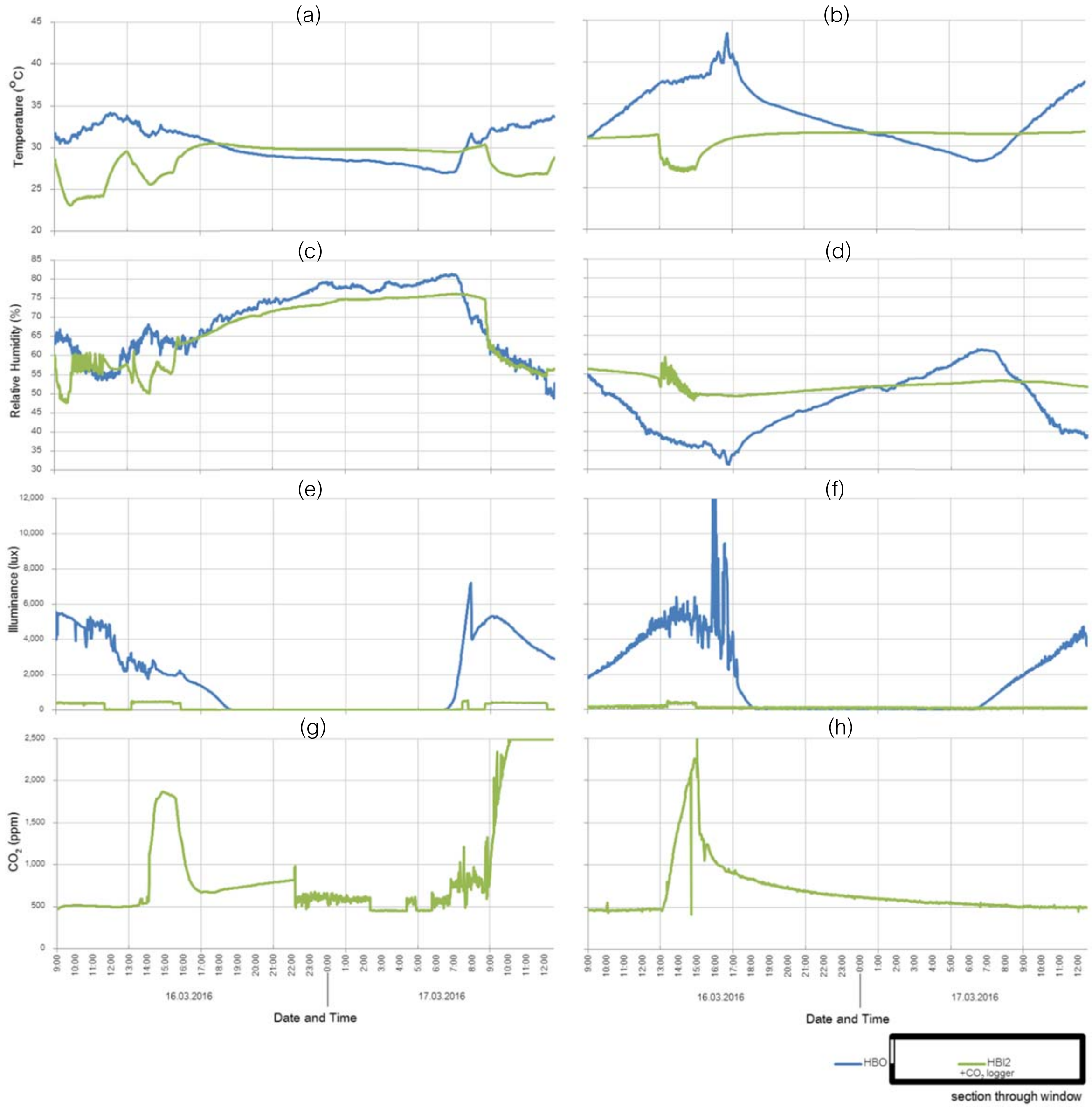


Fig.4. 45 Comparison of measured weather data of 5406A of PSU to the main base case: (a) temperature of 5406A, (b) temperature of AR207, (c) RH of 5406A, (d) RH of AR207, (e) illuminance of 5406A, (f) illuminance of AR207, (g) CO_2 of 5406A and (h) CO_2 of AR207

Expectedly, Figure 4.45 illustrates the RH of the room 5406A which was located on an island in the south that is generally higher than the base case. The unexpected result was the lower temperature, which may be due to effect of direct sun on the base case on 16th of March. As it is shared classroom, 5406A was most frequent occupied comparing to the other cases. The lowest temperature of the room 5406A occurred in the morning of 16th of March that the systems were operated as usual although substantial fewer users occupied. Interestingly, indoor RH of 5406A is close to the outdoor measurement. This occurrence can result in high infiltration of the room and nature of local wind that is generally not only more frequent but also higher speed.

Although weather data have been found different depended on latitude of observed places, measure data in all case studies are not significant different in general. There are some influence factors such as direct sun and air velocity that can dramatically change the weather from its normal pattern.

3) Survey comparison

In order to investigate the similarity of the main case study to other classrooms in the same capacity, different classroom features were studied. The focused parameters consisted of size, façade feature and user satisfaction in themal and lighting (information shown in Table 4.4). When considering each case, there were nothing the same. However, similarity of all cases were found in the ceiling height, the number of seat, and brightness acceptability rate. The main case study is also similar to majority of all cases for room width, room length, window area, glazing SC, thermal sensation and thermal acceptability rate. There are four parameters that the main case study differ to other cases. Apart form the wide corridor, its shading device can shade direct sun less than other cases while brightness sensation and overall satisfaction is in the higher rates.

The differences reveal that the main case study faces less difficultly compared to other case. While the wide corridor and the insufficient shading device were supposed to be disadvantage for daylighting, the participants rated the room bright and satisfied the room the most. Table 4.5 shows more than 0.9 of correlation between all case studies and their average which can imply similarity of each case to each other. The main case study most correlates to the average, Sc SWU and PSU respectively. The fact that Sc SWU and PSU are the cases that correlate to the average the most reveals some unexpected relationships between different features of the case studies. Expectedly, when the parameters of visual comfort and daylighting were considered (Table 4.6), fewer correlations were found in PSU. It is probably because of less exposure of the main windows which is the main difference from the other cases. The main case study, Arch

MSU most correlates to the average.

Tab.4. 4 Focused data of the case studies (all information from the surveys provided in Appendix B)

	Parameters	ARCH MSU	ARCH KKU	SC SWU	SC CRRU	PSU	AVG
Size	Width: W (m.): side to side of students	10.20	9.90	16.00	8.40	7.65	10.43
	Length: L (m.): board to back of students	7.90	13.60	8.60	9.20	12.20	10.30
	Height: H (m.): ceiling height	3.50	3.00	3.00	2.70	3.00	3.04
	Number of seat	60.00	69.00	73.00	53.00	73.00	65.60
	Total width of corridor	4.40	2.20	3.00	2.30	15.90	5.56
Façade	Total area of windows	11.05	59.40	9.66	14.84	15.50	22.09
	Percentage of shading to opimum	57.89	77.78	75.44	85.71	72.22	73.81
	Glazing Shading Coefficient	0.79	0.79	0.79	0.48	0.48	0.67
User satisfaction	Brightness sensation (%)	82.29	75.95	75.05	76.44	76.40	77.23
	Brightness acceptability rate (%)	98.63	99.37	99.33	95.91	90.00	96.65
	Thermal sensation (%)	55.28	51.36	50.19	73.77	54.40	57.00
	Thermal acceptability rate (%)	95.21	95.57	96.67	71.93	83.20	88.51
	Overall satisfaction	80.72	72.24	73.71	68.92	79.94	75.11

Tab.4. 5 Correlation of the five case studies and the average for the room feature

	ARCH MSU	*ARCH KKU*	*SC SWU*	*SC CRRU*	*PSU*	*AVG*
ARCH MSU	1					
ARCH KKU	0.922187563	1				
SC SWU	0.982518449	0.931359146	1			
SC CRRU	0.944491712	0.907656322	0.949778745	1		
PSU	0.978588736	0.92860773	0.984691959	0.956566657	1	
AVG	0.986213359	0.957809146	0.99037943	0.97168671	0.990114699	1

Tab.4. 6 Correlation of the five case studies and the average for the visual comfort and daylighting

	ARCH MSU	*ARCH KKU*	*SC SWU*	*SC CRRU*	*PSU*	*AVG*
ARCH MSU	1					
ARCH KKU	0.959247	1				
SC SWU	0.980287	0.92862	1			
SC CRRU	0.98143	0.978115	0.965998	1		
PSU	0.757746	0.609078	0.702935	0.623572	1	
AVG	0.988983	0.975242	0.983299	0.98272	0.689686	1

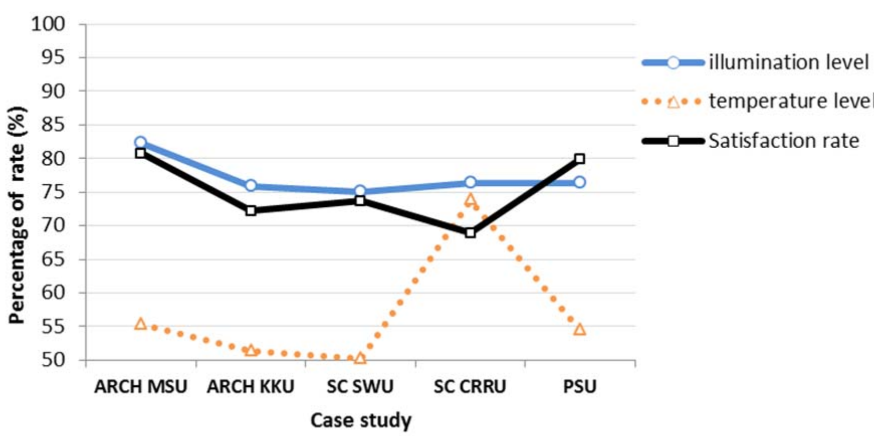


Fig.4. 46 Percentage that participants of each case study rate for illumination level, temperature level and satisfaction rate

Participants answer question in the same questionnaire shown in appendix A. In classroom observations, physical problems and users' response generally agree to the answers. Figure 4.46 reports sensation levels comparing to overall satisfaction rate. Questionnaire participants rate their lighting sensation in their classrooms between 75.05 - 82.29% in average which is in the range from ‘slightly bright’ to ‘bright’. For thermal sensation, participants in most cases rated their classrooms between 50.19 - 55.28%, from ‘comfortably cool’ to ‘comfortable’. The only case that was rated in the range between ‘comfortably warm’ and ‘too warm’ is room 5111 of Sc CRRU. The similar results of majority are because all classrooms generally operate air conditioning system which setting temperature at 24-26ºC. The room 5111 of Sc CRRU has been used without air conditioning system because the system is frequently out of order and electrical fans were decided to use instead of replacing the AC. Overall satisfactions were rated between ‘slightly satisfied’ and ‘satisfied’ in most cases. Only the room 5111 of Sc CRRU was rated slightly lower than ‘slightly satisfied’ level. The result confirms conclusion of the main case base that thermal sensation has more impact on overall satisfaction than lighting aspect. However, some frequent comments reveal other factors that influence overall satisfaction. There are quality of teaching devices, room furniture and decoration and availability of building systems. Interestingly, other interesting comments are air quality and the need of natural ventilation.

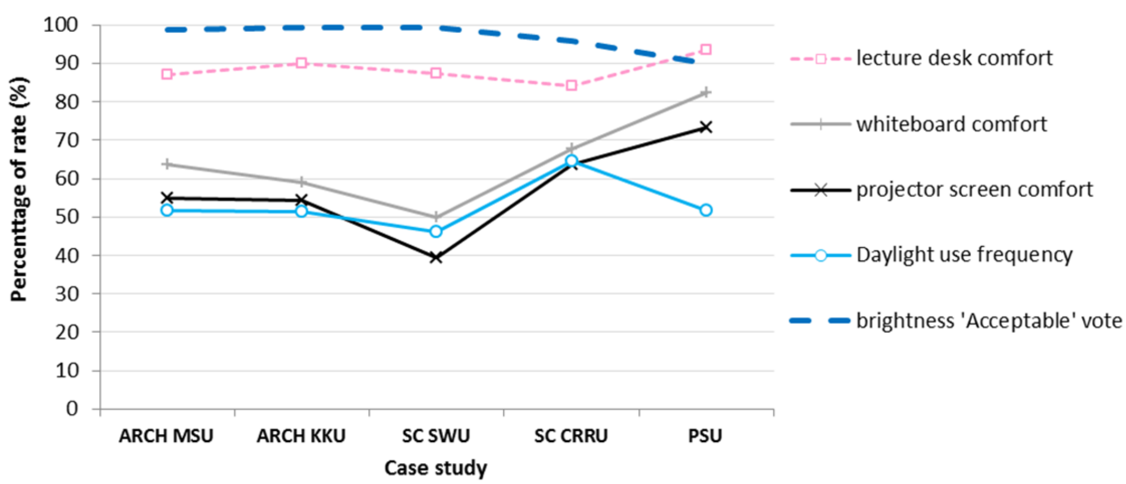


Fig.4. 47 Percentage that participants of each case study rate for visual comfort of the three tasks, daylighting use frequency and brightness acceptable vote.

The visual comfort problems which were found were very similar, although the participants rated their classrooms differently (shown in Figure 4.47). The main problems of the case studies were that the lighting environments were rated as either too bright or too dim. This type of comment is in doubt, especially when majority of participants prefer bright condition. It can be because of excessive high brightness contrast and use of different devices. There were comments in most case studies that the brightness for seeing a task on the lecture desk was generally too bright. The only case that participants said was too dim was 5406A of PSU, which contains a small window area. For using whiteboard and projector, the rate of visual comfort and specific comments are similar. Veiling reflection from the window on the whiteboard was mentioned in the opened question of all cases while the main issue of seeing projector screen is about low quality of device and media. Lighting problems cause visual discomfort for projector use are lighting disturbance and improper lighting environment either too bright or too dim resulting from inappropriate lighting and daylighting integration.

Almost all cases sometimes used natural light, except 5111 of Sc CRRU, for which daylight was used more frequently. It is because of not only limited room width but also no internal blind. For daylighting, some participants who sit near windows said general room brightness was too bright while it was too dim in the rear area. For lighting integration, too bright and too dim conditions area were also the comments of all cases when the light was switched on and off respectively. However, all case studies rate room brightness acceptable in very high percentages.

4.6 Discussion

Using surveys and measurements, visual problems of the case study classroom were monitored and investigated. Four major issues were raised as significant for this study. They are existing façade problems, behaviour of façade and system operation, requirement conflicts of main visual tasks and practicality of standards.

1) Illumination issues from existing façade

When all survey and measurement were considered, the existing façade was found inappropriate. The majority of participants rated daylighting condition the worst case in terms of glare occurrence. According to the measurement, illuminance of the case study in daylighting environment rarely met the standard of 300 lux. An area about 1.2 metre wide and five metre deep from the window in summer solstice and winter respectively that illuminance more than approximated to or higher than the standard. It implies that although it is lowest altitude sun in winter solstice and the window high stretched to room ceiling, the optimal deep of the room should be five metres. When compared to Steemers (1994)'s suggestion, which is six metre deep, the case study experiences little lower. Additionally, uniformity ratios are also much higher than the standard of 0.8. An insufficient quantity of daylight probably results from the narrow shape of the room. Apart from additional windows in other sides that was suggested to be included (Steemers, 1994 and Tanner, 2000), a large window area is also required for narrow rooms (Ghisi and Tinker, 2005). The window area at 31.5% of wall area or 9.65% of floor area of the case study is in the range of recommendations. The area appears to be lower than previous studies in daylighting (Buriprasert, 2000 and Chungloo et al., 2001b) and higher than the studied that integrated with thermal aspects (Maitreya, 1979; Chirarattananon et al., 1996 and Binarti, 2009). However, the recommendations may be in a similar climate but is definitely in different contexts, especially regarding window orientation and shading device. For this study's context, the window area appears not large enough for daylighting.

Facing the southwest, the room was normally affected by the highest illuminance in the afternoon when the classroom was generally occupied. According to sun path of 16°N the sun altitude is at a low angle in the afternoon for most day of the year in the southwest, except during the summer when the sun normally affects north orientations. Occupants' comments show that they had been generally disturbed by the light from window. This information reveals that an overhang acting as an external shading device that is 2.1 metre deep is probably too small for this orientation. The curtain was found to cause insufficient illuminance problems. Moreover, its condition was of it almost never being opened. The device therefore is possibly impropriate. According to Dubois (2003), an overhang was classified in the group of devices that provide highest illuminance but it provided the poorest uniformity ratio. David et al. (2011) affirmed that an overhang performed best for sunlight protection in a north orientation while it is louvers for west facing. The results reveal a good performance of horizontal device in terms of sunlight protection especially when its depth is sufficient. Overhangs may provide better results if it is an optimum depth. However, the research also pointed out that only horizontal device is not enough in terms of visual comfort. Not the screen type like curtain but louver and venetian blind were confirmed best solutions for glare controlling. Consequently, external horizontal device with internal venetian blind can be proper solution for daylighting in tropics. The blind is required to be adjustable for not only daylight fluctuation but also the use of ICT media.

Direct sunlight had been widely avoided especially in the tropics. However, Edmonds and Greenup (2002) partly disagree and state that sunlight penetration can benefit lighting environment if it is in an appropriate amount that does not cause thermal discomfort and glare. Boubekri and Boyer (1992) informed that when window is in a side of the occupant occurrence of glare is rare although sunlight penetrates into the room. For good daylighting, the studies reveal that penetration of direct sun should be allowed but in proper proportion. Not types but projecting deep of shading device is the basic principle of design that relate to amount of sunlight penetration. For horizontal shading type, proper deep of any basic shading type such as overhang should be investigated.

For orientation, the case study building contains lecture rooms only in southwest and northwest orientations. While Zannin et al (2008) reported the benefit of ordinal orientations that allows more exposure to daylight, it was found worse for daylighting in a southeast classroom according to (Saihong and Srisutapan (2007). In addition, occupied time is an important factor of orientation impact. Intarakulchai (2013) who investigated daylighting in studio spaces in the same building of the case study how the result that additional window in southeast orientation provide no significant difference of the studio daylighting distribution since the sun effect east orientations in the morning when the room was generally unoccupied. In the case study, differently, the classroom was generally occupied both in the morning and afternoon. Moreover, the sun more frequently effects south than north orientations, therefore, it can be either advantage in terms of daylight availability or drawback for heat and glare controlling.

When considering impact of existing façade elements, orientation appears to have the highest impact as different orientations can provide substantially different illuminances. The difference cause by strong summer ambient light intensity dominated the northwest facing while being less influential on the southeast. It implies a hidden influential façade parameter which is the time and season changes. Lighting integration also has high impact on improving lighting level but the level was generally much higher than standard whether there is natural light or not. Overestimate of artificial light appear to be occur in classroom in general (Winterbottom and Wilkins, 2009) and it is doubted in terms of energy conservation. Impact of curtain appears to be the least because it cannot improve lighting environment. However, occlusion of the device can dramatically reduce illuminance and remain one of daylighting barriers.

2) Occupant behaviour and façade operation system

In the case study, the classroom occupants generally had positive attitudes in using natural light. It can be a good sign for daylighting if they are operating windows. However, it was found that they were not. One of the reasons can be it is difficulty to operate the device. The operation system controllers are located far from the teachers who dominated the class. A more important reason, agreeing with De Giuli et al. (2013), is that students who faced more visual affects tended to accept unsatisfactory conditions rather than notify the teacher the problem. According to Boubekri and Boyer (1992), they will express their discomfort only if it is extreme. Moreover, some literature informs that they may not notice and delay response (Rea, 1984).

Automatic system may be able to solve this problem but manual system was strongly recommended for classrooms in or der to control lighting level in different teaching media (according to LEED (USGBC, 2009) and BREEAM (BRE, 2011)). While manual system is required but the occupants cannot correctly estimate the illuminance, some support systems that can facilitate teacher operate façade and lighting systems should be suggested and their controller should be place near teacher's position.

Improper lighting from the daylight and artificial light is also the problem. Opened blind condition could not provide good lighting environment for the classroom. Lighting layout which was design parallel to window line may optimise lighting level of the room and brought fair uniformity but agree to Hunt (1979) the occupants almost never partly applied the light. The system also cannot solve application of ICT devices. It is Lack of research focusing in lighting layout. Existing studies (e.g. Chou et al. (2004) suggested lighting integration using the same concept of the case study. However, rather than the daylight, teaching media appears to be the main factor of the system operations. Theodorson (2009)'s study support this statement.

3) Daylighting for the three visual tasks

The participants assessed daylighting environment that it is fair visual comfort for task on lecture desk, less comfort for white board use and most comfort for seeing project screen. Application of artificial light can improve lighting condition for lecture desk and white board while blind occlusion benefited projector use. It reveals that room illuminance may be insufficient for lecture desk but fair for using projector and taking note at the same time. The weakness of side lighting providing unqualified light environment in terms of quantity and quality Alrubaih et al. (2013) appear to be overstatement for ICT media tasks. The use of a white board appeared to be limited for integrate with the use of projector because either closed curtain off light condition brought inadequate illuminance or use of daylight frequently cause veiling reflection. Winterbottom and Wilkins (2009) stated that high illumination level can solve the veiling reflection problem. It may agree to the artificial light conditions, but it may not appropriate for seeing projector screen simultaneously. Suggestion of Tangpoonsupsiri (2001) to tilt the devices alone may be more sensible to solve the problem. All satisfaction votes of the projector task has to be noted that it may include the equipment quality which was related to the three criteria suggested by Ramasoot and Fotios (2009) more than lighting conditions.

4) Standards and occupants' satisfaction

The occupants of the case study rated other aspects such as thermal comfort to be priority resulting in visual aspect ignorance. This result differs to Boubekri and Boyer (1992) stating that classroom occupants emphasized their visual proplems more than thermal aspect. It could be differences which cause by climates. It may be concluded in this case that people in cold weather zone may place visual comfort more important than that in hot climates while people in hot climates are sensitive with thermal more. However, existing evidance may not enough to generalise the findings. The majority of case study occupants also prefer bright environment. Accordingly, Denan (2004) also pointed out that occupant in a classrrom in malaysia prefer bright condition and the result was noted that may be different from other climates espacially in Europe and North America where most of lighting recommendation has been widespead published. Consequently, impractical of those recommendation was impied. Moreover, some research such as Ramasoot and Fotios (2009) claimed that some of recommendations are out of date particularly for ICT classrooms. Simliar results were reported (e.g. Wu and Ng, 2003 and Alrubaih et al., 2013) that daylighting evironment is different from articial lighting spaces. Because most of recommendations was created in artificial lightin condition, it also has errors when applying to daylighting conditions.

For illuminance, the participant perferred the range of approximately 300-500 lux that they vote it is bright condition. It may be able to confirm practicality of the standard but interestingly the range of about 100-150 lux was rate neutral. It reveals that the lighting environment in this range is acceptable. It similar to the lower thredhold of UDI (Nabil and Mardaljevic, 2006) and the first rating scale of LEED 2009 (USGBC, 2009). However, it is little lower than recommendation of daylighting space of National Research Council of Canada (Alrubaih et al., 2013). The threshold of 300 lux appears still sensible while it can be flexible to be lower. However, range from 100-300 lux is recommended for computer task in CIBSE and Cen code of 2002 (da Silva et al., 2012) and general use recommended by IES lighting code 1955 (Wu and Ng, 2003). In the survey, there was no circumstance that participant vote excessive high illuminance. It might be due to the fact that the maximum illuminance during the survey is lower than 700 lux. For upper threshold, UDI applied 2,000 lux which concordant to maximum value of retina (Altomonte, 2009). Therefore, the range of 300-2,000 lux should be considered in general and it can be expanded to be 100-2,000 for some casual learning activities.

Similar to previous research such as Chou et al. (2004) and Piderit and Bodar (2012), neither general uniformity standards of 0.8 nor the newer suggestions by the researchers which are 0.5 and 0.6 are practical. The combinations of daylighting and lighting which provided uniformity ratio at 0.24 and 0.49 also were voted as comfortable conditions.

While illuminance ratio was generally recommended in the range of 1:3-1:5, range of illuminance ratio of participants' preferable conditions is normally little larger at 1:2.79-1:5.81. However, there were some dim environment cases that caused participants to be dissatisfied but the ratios met standards. With limited evidence, the recommendations appear to be sensible but not for dim environment. Consequently, the use of ratio should be included information that can demonstrate sufficiency of lighting level.

For luminance ratios, the measurement are partly different to the survey. The ratio of projector screen to adjacent backgound was found generally in standard of 3:1 for articifial lighting environment and the condition also was the participant's preference. While daylighting conditions which was rate acceptable may provide little higher ratio than 3:1 but approximate to acceptable level suggestion of Cantin and Dubois (2011) at 6:1. The dimmest conditions of closed curtain off light rather caused excessive high ratio and participants' dissatisfaction. It reveal that the use of projector screen may not required too dark lighting conditions. The ratio of maximum to minimum was doubted. The acceptable condition of daylighting environment was generally over the standard of 40:1 while the less dissatisfaction environment performed better ratios. Unexpectedly, the artificial light condition provided just fair ratios despite no effect of daylighting. The ratio can be acceptable unless there are conficts of the ratio and participants' preference. Moreover, the difficulty of the measuring process may cause errors. Although vertical luminance can be a better indicator of visual confort, this metric was avoided as more comprehensive investigration is required.

5) Problem generalisation

When illumination issues from existing façades of the main case study were compared to the additional case studies, similar difficulties were found, although existing façade features were different. Daylighting alone cannot achieve the lighting requirement of 300 lux in working hour of the survey date. The room with minimum width, 5111 of Sc CRRU, appears to have maximum internal illuminance but the illuminance was lower than the standard for some times. Moreover, too dim an environment was raised in the survey. Three cases with opposite side windows which supposed to provide sufficient illuminance, but the problems remain due to similar reasons as the main case study: insufficient window area and internal shading device.

In terms of window orientation and sufficiency of shading device, the problem of direct sun penetration appears not as severe as the main case study which faced to the southwest. The case studies facing to the north contain overestimated external shading devices while external devices are inadequate for the southeast and east orientations. For the cases with insufficient shading, opaque blinds of the rooms can solve the problem. Although there is no comment about sunlight disturbance, the effect of intensive light from the windows is also one of the main problems for seeing whiteboard and projector. Apart from low quality of teaching devices, improper lighting lay out is frequently reported as problems.

Teaching and learning behaviour of all classrooms were similar, except in working hours in that some case studies started one hour early and later than the main case study. The classrooms with curtains were always used with closed curtains and fully switched on lighting condition. The classrooms with tilt glazing contained on blind but also always applied artificial lights. The problems in the three visual tasks were also similar to the main case study. Too dim an environment was the main problem for reading tasks on lecture desk. Too bright condition and improper control of light source frequently disturbed the use of projector. For seeing the whiteboard, the occurrence of veiling reflections was the key comment in all case studies. While occupants' satisfactions in their classrooms were different, brightness satisfaction rates approximate to each other. The additional comments that reported problems in terms of brightness and visual comfort imply that the satisfaction result may overestimate. Survey results in all cases reveal less significant of visual comfort than other aspects such as thermal comfort.

To sum up, visual discomfort results from various causes. Some of the main reasons, such as quality of teching materials and devices, have to be excluded because it is not in the scope of daylighting. When lighting enviroment in the three visual tasks was considered, the factors of façade for daylighting were limited. For the uses of whiteboard and projector, the daylight appeared to be a proplem due to the position of its source and its intensity. The daylight was required to be controlled when using whiteboard and projector. For general use and seeing tasks on lecture desks, adequete and uniform daylighting is required. In order to deal with the conflict, classroom façade has to be able to enhance illumination level and uniformity while can be adjusted for controlling the daylight. For studying daylighting façades, the problem of an existing façade should be further examined for the impact of direct sun and relationship between four parameters: time and season change, window area, shading size and window orientation using very basic metrics in order to provide simple format to compared with thermal aspect. Apart from quantitative findings, satisfaction results should be collected in order to validate visual comfort which the quantitatives result cannot do.

Chapter 5

Predictions

For the four focused façade features (window area, shading device, window orientation and reflected strategy), it is with the first three parameters that DesignBuilder is compatible with. According to simulation results, there are five main interesting points that can show availability of daylighting and priority of the parameters. Apart from the focused parameters, seasonal aspect and more window side were included in order to examine how much of the most possible daylight that the façade can transfer into the room. Importance of the parameters will be found in this part with significant relationships of them in addition.

5.1 Availability

Before studying the focused parameters, two pilot studies were studied for investigating differences between existing classrooms and daylighting availability in those rooms.

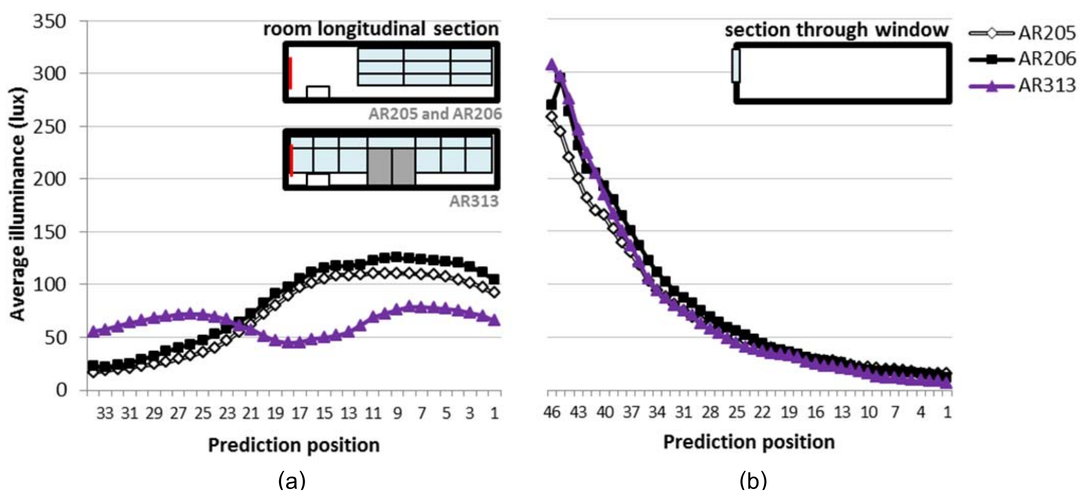
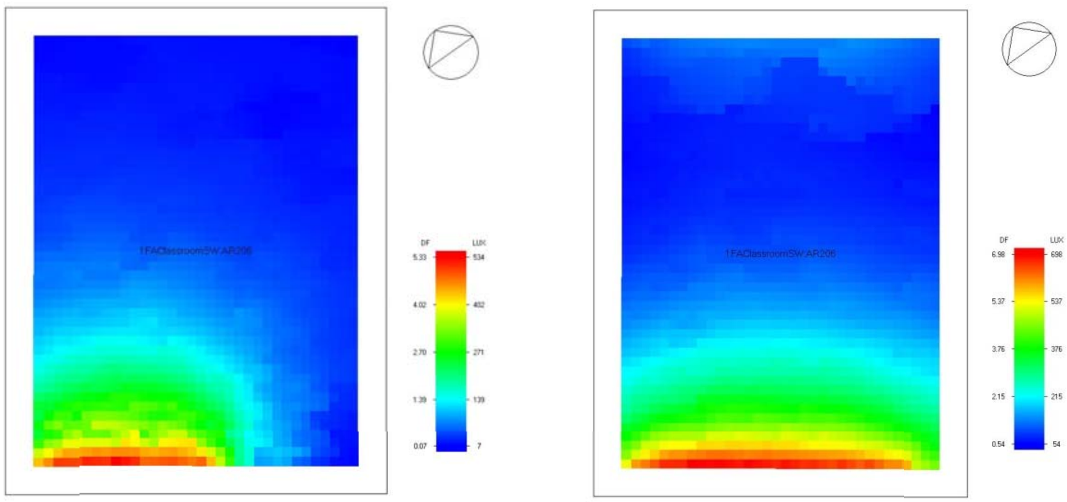


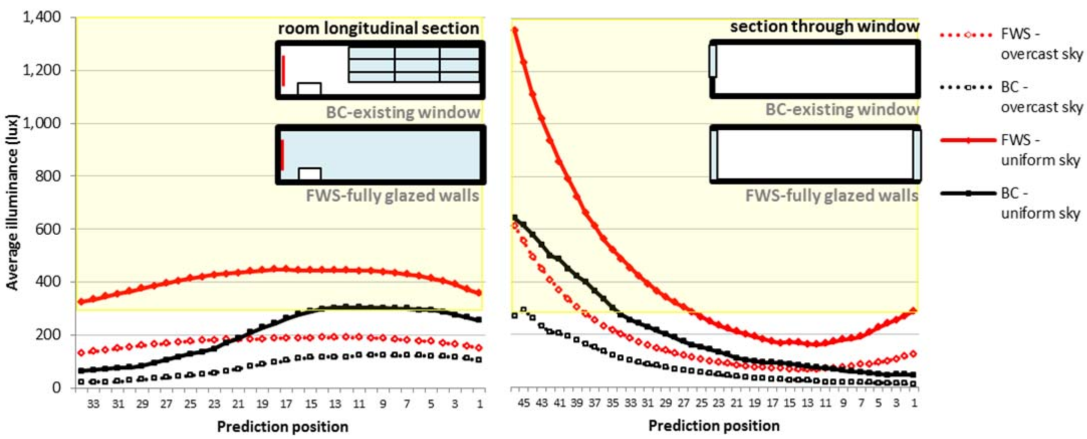
Fig.5. 1 Comparison of illuminance prediction for three focused room in overcast sky: (a) average for room longitudinal section and (b) average for section through window

The prediction for existing classrooms was compared in order to confirm that the result in this study can represent all 60 seat lecture rooms in the building. Three representatives: AR205, AR206 (base case) and AR313; were compared in Figure 5.1 for overcast sky conditions in order to avoid the influence of direct sun. In other words, the rooms were simulated under overcast sky condition which contained no effect of direct sun. Without the influence of sun geometry, average illuminances of the room in different positions and orientations are similar (see Figure 5.1(b)). The different pattern between AR313 in northwest orientation and the other cases in southwest facing shown in Figure 5.1(a) are caused by the window appearance rather than the influence of orientation. Although their distributions are not the same, they approximate on average.



(a) (b)

Fig.5. 2 Illuminance distribution of AR206 with: (a) existing window-base case and (b) two opposite wall fully glazed in overcast sky condition.



(a) (b)

Fig.5. 3 Comparison of AR206 illuminance between room with exiting window-base case and with two opposite fully glazed wall in overcast and uniform sky condition: (a) average for room longitudinal section and (b) average for section through window

For availability, the skies with average minimum and maximum illuminance (overcast and uniform sky conditions) were analysed. The results in Figure 5.3 shows that illuminance of the base case is insufficient in general. Only the area near the window, daylight level meets standards. For the maximum case, only two opposite site wall includes in building envelope. Most feasible case that can maximize daylight into the room is two opposite fully glazed walls. The result demonstrates that when applied the fully glazed walls with existing elements most area of the room had sufficient illuminance for a uniform sky (Figure 5.3(b)) while for overcast sky only one fourth of the room that daylight level meet standard (Figure 5.2(b)).

Pilot studies reveal that only one classroom can represent all lecture rooms in the same type in general. AR206, which is the base case in measurement and observation stages, was selected to be the main model for simulation. Daylight appears insufficient for the existing façade feature, but it is possible to improve lighting environment more sufficient only by changing the façade. The proven solution will be presented in the next part when influential parameters were intensively studied.

5.2 Assessment criteria

According to literature review and the results of survey and measurement, some of daylighting metrics were discussed: illuminance threshold, UDI, illuminance ratio and luminance ratio. Some visual comfort indexes such as glare index were excluded because of limitation of techniques and existing devices. Apart from simple measurement devices, DesignBuilder package may provide a lot of functions for thermal and energy aspects but can predict only horizontal illuminance distribution for daylighting. As an additional reason, the indexes have been doubted because the results also show quantitative rate of visual sensation and probably not absolutely indicate real visual discomfort. This research, therefore, attempted to simplify basic ideas of the major cause of visual discomfort which are excessive high illuminance from the light source and variation of daylight distribution.

For lighting quantity, threshold of illuminance was focused on. It is a standard of 300-500 lux for lecture rooms in general. The standard was verified in the survey and measurement that provided desirable visual environment in many lighting conditions. However, lack of excessive high illuminance case that can confirm practicality of UDI upper threshold. A 2,000 lux threshold, therefore, was applied in this research. An idea of '*percentage of the room that illuminance more than 300 lux and less than 2,000 lux*' was developed from the UDI concept which is percentage of useful daylight level for a whole year. In this study, daylight distribution in each working hour was focused. The 'percentage of the room that illuminance more than 300 lux and less than 2,000 lux' considered amounts of pixel that illuminance meet the standards from 34*46 pixels of predicted daylight distribution in each hour. The day result is an average of the eight slots of working hour: 9AM-4PM. The general threshold of UDI which is 50% also was applied.

The amount of daylight was considered with thermal aspects: Fanger PMV rate and cooling load. For Fanger PMV, the comfort rate is in the range between -0.5 and 0.5 while Fanger's recommended comfort zone ranges from comfortably cool (-1) to comfortably warm (1). In this study, the range of -0.5 to 0.5 was applied although it appears too strict for all cases. Actually, neither -0.5 to 0.5 nor -1 to 1 are sensible even for winter in Thailand. However, this is because the weather in Thailand is normally too warm. Comfortable thermal environments are very rare. On the other hand, the program was proven generally overestimates air temperature and RH. Prediction of thermal comfort rate possibly also overestimates. For this reason, either the results are actually cooler than predictions or the range of standard can be wider than the recommendations. According to empirical survey, occupants appear sensitive to thermal discomfort more than lighting and they prefer cool than warm. This asymmetry satisfaction may cause the prediction more distance from occupants' comfort. The use of comfort rate may be questionable, the range of -0.5 to 0.5 then was applied in this research only for comparing the different between prediction and theoretical comfort area. When cooling load was considered, there is no standard can indicate what extent of decreasing cooling load is most efficient. Only CHPS (2006) suggested that 10% of the standard design should be reduced for energy conservation. In order to reach that target, many strategies are required. Only façade feature and cooling load appear insufficient. In this research, the cooling load of the base case was applied to be benchmark. The plus value stands for the case that cooling load is more than the existing classroom while the number will be shown in minus if cooling load is lower. The values applied in percentage of increasing cooling load from the base case.

For visual comfort, an illuminance ratio was applied representing a range of illuminance differences that may cause discomfort. These are 1:3 and 1:5 that had been recommended and they have been verified by the survey and measurement as acceptable except for the cases of too dim an environment. However, the standards appear too strict for predictions for all cases. It is probably because the program generally overestimates all of high illuminance levels distributing near the window for about three too ten times of actual illuminance from the measurement. The overestimated illuminance definitely includes the maximum illuminance. Considering the standards with the proportions of excessive rate, the ratio was modified to be 1:10, 1:20 and 1:50 (about three times of 1:3, three and ten times of 1:5) for the level recommended, acceptable and tolerance. Interestingly, the ratios are similar to luminance ratio recommended by Cantin and Dubois (2011). Due to the fact that, illuminance ratio is not reliable when the light environment is too dim. It always has to be considered with illuminance level. Fortunately, lack of too dim environment was predicted in simulation stage.

Tab.5. 1 Summary of standard used for simulation results.

No.	Metric		standard		Note
			Original	Used in this study	
1	Illuminance (lux)	Minimum threshold	300	300	Has been verified by survey
		Maximum threshold	2,000	2,000	Possibly higher up to 6,000 due to overestimated prediction
2	Percentage of the room that 300<illuminance<2,000 lux		50%	50%	The metric was modified from UDI
3	Illuminance ratio (min.-to-max. ratio)	Recommended	1:3	1:10	Modified using regression formula for only maximum illuminance with is overestimated.
		Acceptable, Tolerance	1:5	1:20 1:50	
4	Thermal comfort threshold	Comfort range	-0.5 to 0.5	-0.5 to 0.5	Can be little higher because some thermal comfort factors were found overestimated
		Fanger's suggestion	-1 to 1		

Table 5.1 shows the selected standards applied in this study comparing to original recommendation. They are used in the following part that analysis of simulation results will be illustrated.

5.3 Differences by period of the year

Representing different season in the whole year, specific dates: the dates that the sun vertically overhead, equinoxes, summer and winter solstices; were applied to investigate difference of predictions. Expectedly, the three indicators which are illuminance, Fanger PMV and cooling load will be differently predicted due to the weather and influence of the sun. Fig.5.4 shows predictions of the existing façade type comparing to the most critical case which is the most window area case without shading device. Average illuminance of the room appears to reduce to the lowest in summer solstice then increase and reach the peak in winter solstice (see Figure 5.4(a)). Figure 5.4(b) presents that the highest Fanger PMV rates are in summer solstice and March equinox while the minimum is on winter solstice. These results concur with total cooling load predictions in Figure 5.4(c) that is maximal in summer time and minimum in winter solstice. It also reveals that the significant period of the year which can be used to represent the maximum and minimum predictions are winter and summer solstice although the dates that the sun is vertically overhead appear to be the warmest days.

When considering the existing façade as a base case, room average illumination levels appear to meet the standards, but minimum illuminance of the room are totally insufficient (Figure 5.4(a)). When the air conditioning system was not applied to the simulation, the results of Fanger PMV in Figure 5.4(b) reveals the need of cooling system as it is warm in average and hot to very hot in summer. In terms of cooling load, the year average load is 9.13 kWh while it reaches the peak at 16.82 kWh in summer solstice (shown in Figure

5.4(c)). The case of two opposite fully glazed walls without overhang was assigned to represent the most critical cases that the daylight and heat gain can be transferred the most. As shown in Figure 5.4(a), minimums of room illuminance are slightly lower than standard of 300 lux which probably acceptable unless the averages are excessive higher than the upper UDI in most of the year. The illuminance also much more than the base case in all period: the differences are from about 700 lux in summer solstice to 6,000 lux in winter solstice. It is possibly due to influence of direct sunlight. Fanger PMV and cooling load of the two fully glazed case are slightly higher than the base case and the differences of each specific dates approximate to each other which are about 0.5-1 scale of Fanger PMV and 2-4 kWh of cooling load (Figure 5.4(b) and (c)).

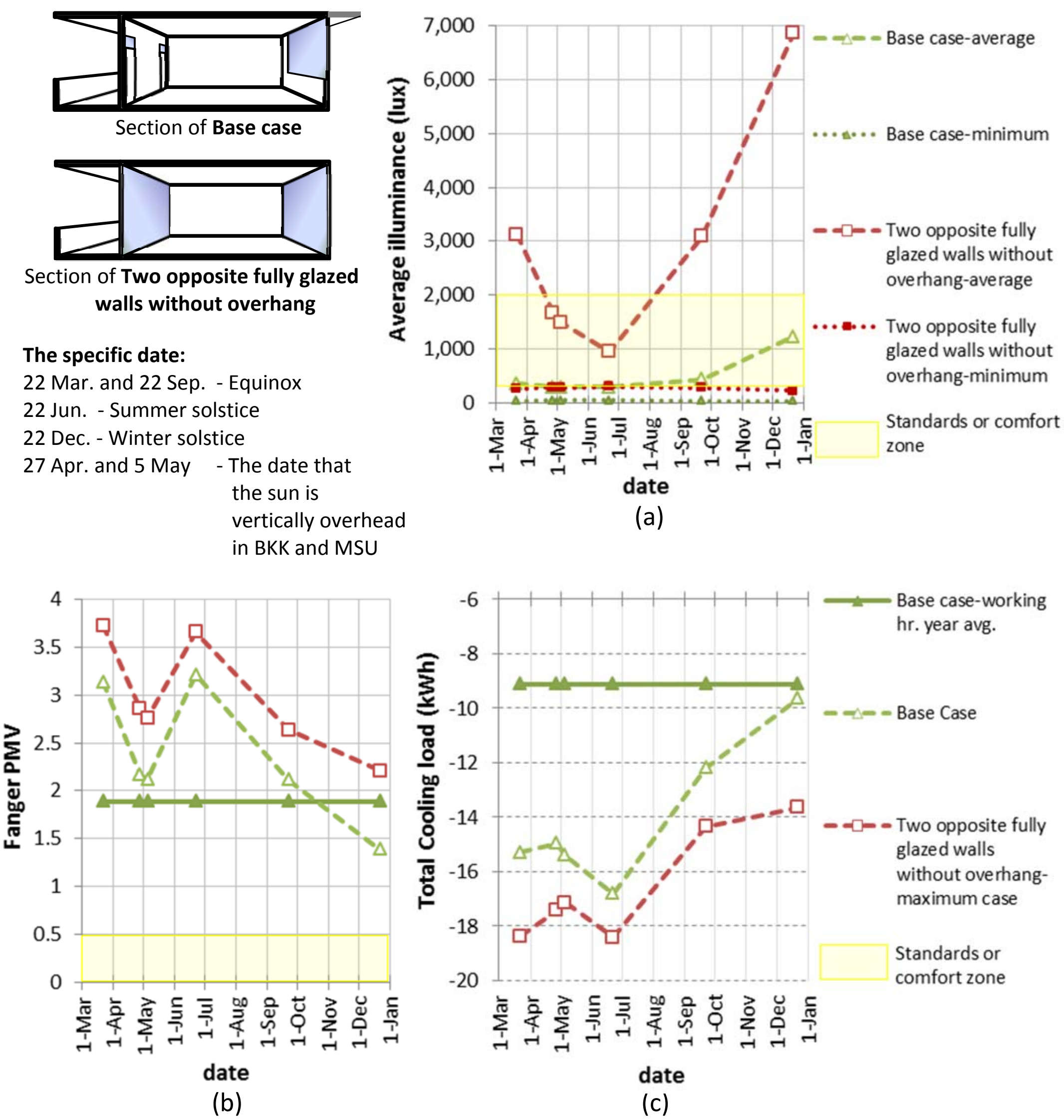


Fig.5. 4 Predictions of base case compare to the most critical case in the six specific dates of the year (a) average illuminance, (b) Fanger PMV and (c) total cooling load (generally predicted as negative value)

These results might show that the existing façade seems to provide adequate illuminance in average though the minimum illuminance shows that it is insufficient in some areas of the room. Moreover, the result probably resulted from the average of excessive high and insufficient illumination levels. The minimum illuminance of the room with two opposite fully glazed walls can be a practical solution as it is approximate to the standard but average illumination levels of the room are mostly excessive high. According to Figure 5.4(a), both minimum and average illuminance are acceptable during April to August when the angle of the sun is bigger than the rest of year. In order to deal with dissimilar daylight levels due to effects of direct sun, adjustment of sun shading device could be a possibility. The results also imply that exposure of direct sun into the room influence daylight level more than thermal aspect.

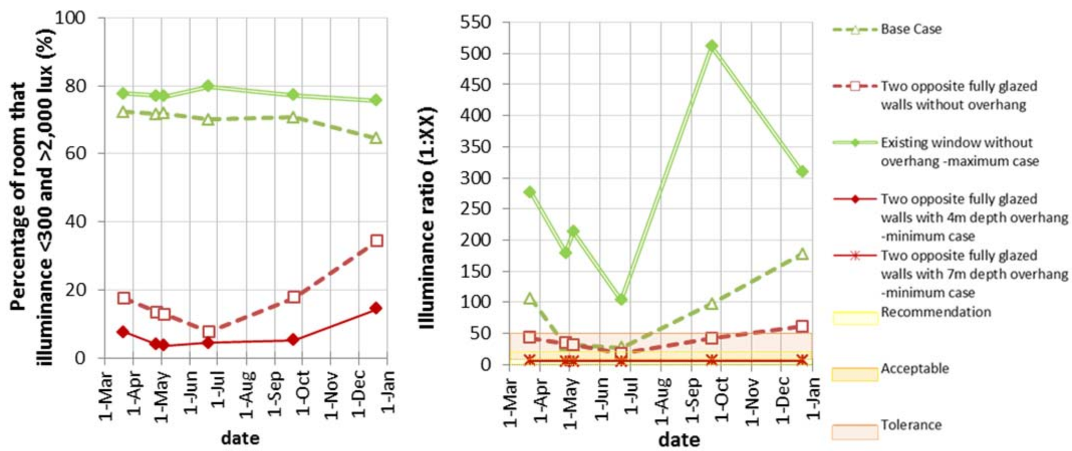


Fig.5. 5 Predictions of base case compare to the most critical case in the six specific dates of the year (a) percentage of room that illuminance does not meet the standards and (b) illuminance ratio

When daylight distributions of the room are considered, 'percentage of room that illuminance does not meet the standards' was assessed. The term stands for how many predicted positions of the room that working plane illuminance is lower than 300 lux and higher than 2,000 lux. It can be seen in Figure 5.5(a) that there is no significant difference of the percentage of room that illuminance does not meet the standards thorough the year for existing window cases while the maximum difference occurs in the two opposite fully glazed wall without overhang case. It is about 30% between winter and summer solstice which probably due to influence of direct sun. The high percentages of the existing window cases mainly cause by insufficient illuminance. In other words, the area of the existing case could be inadequate for providing the daylight even if it is no shading device. For the two opposite fully glazed cases, the percentages are substantial low as more daylight was provided. The percentages increase to the highest in winter solstice due to impact of excessive high illuminance of direct sunlight. In terms of ratio of maximum and minimum illuminance (shown in Figure 5.5(b)), the two opposite fully glazed walls cases also bring about low ratios although direct sun is totally allowed in the case without shading. The ratios of the two fully glazed walls without overhang are tolerance excepted in summer and winter solstice. It is acceptable for summer solstice and over tolerance level for winter solstice. For the two fully glazed walls with a seven metre depth overhang, it is the lowest ratios compared to other cases. The ratios are steady in the recommendation level. On the other hand, majority of ratios of existing window cases are more than tolerance. Only for the base case, the ratios are in tolerance level during April to July. Existing window without overhang is the most critical case for illuminance ratios as not only the illuminance ratios are substantial high comparing to other cases, but the daylight distribution is also generally lower than the standards.

To sum up, there are two periods of the year which can be used to represent the worst cases for thermal aspect and daylighting. The period during summer solstice, the predictions are in very hot scale of Fanger PMV resulting in the peak of cooling load while the room averages of daylight level are the lowest. Fortunately, due to less impact from direct sun, the illuminance ratios are normally the lowest. For winter solstice period, cooling loads are the lowest as Fanger PMV rates are close to comfort the most whereas illumination levels are considerably high. The direct sun not only causes considerably high illuminance, but it also causes overwhelming illuminance ratio. The difficulties can be solved separately by application of shading device for winter and most exposure for summer. The solution for summer should be carefully applied because it may also increase load of cooling system.

5.4 Window area

With existing overhang, three window area cases: the room without window, with existing window and with fully glazed wall; were examined. The no window case (0%) and fully glazed wall (100%) were selected to be reference points as there are exactly the minimum and maximum cases. 31.5% of fully glazed wall is the window area of existing window. As shown in Figure 5.6, it is almost linear relationships between window areas for the three indicators. For illuminance shown in Figure 5.6(a), all cases in overcast sky are lower than the standards while the fully glazed wall is too high in winter solstice of sunny clear sky. Room illuminance might not enough for low brightness sky conditions like overcast sky while for both winter and summer solstice in sunny clear sky illumination levels of window area of about 35-82.5% meet the standards. In terms of thermal comfort, there are slightly differences between each window area.

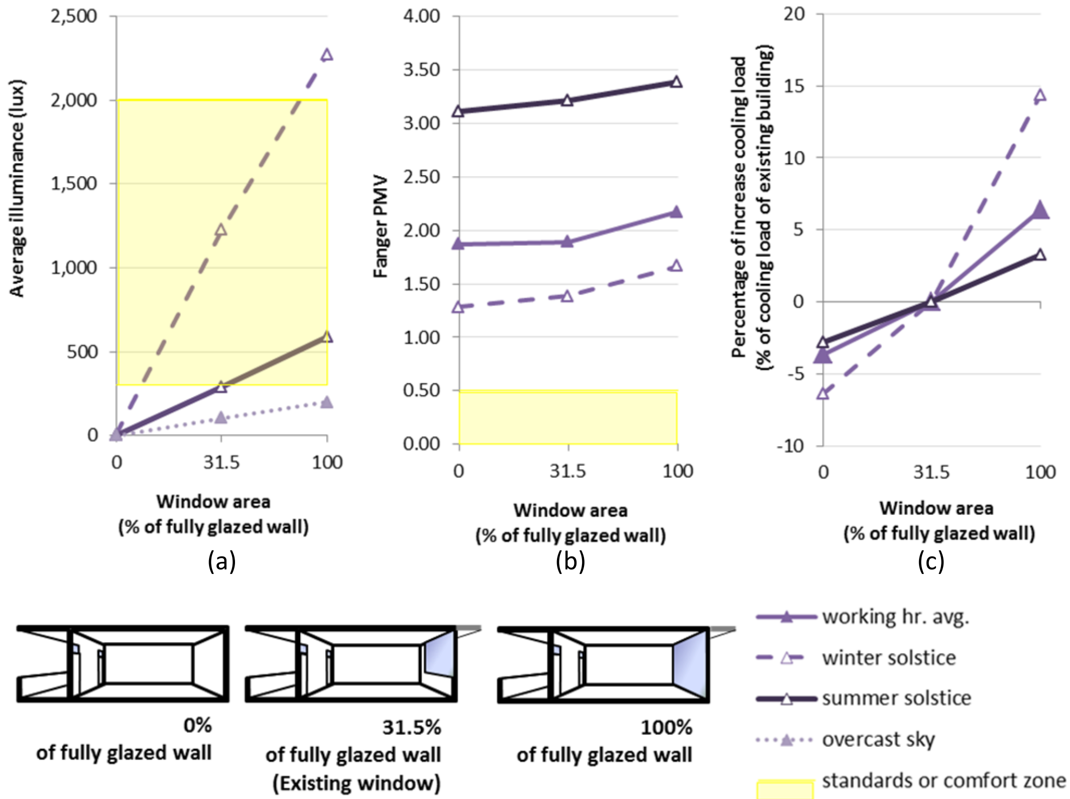


Fig.5. 6 Impact of window area and different weather of winter and summer on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

The differences of Fanger PMV between 0% and 100% window area are lower than 0.5 scales (see Figure 5.6(b)). Although Fanger PMV scale in summer solstice is much higher, the percentage of increase cooling load of the existing case in winter and average are less than that in year averages and winter solstice for 100% window area (Figure 5.6(c)). The comparison of three different overhang depth cases in Figure 5.7(c) reveals that the issue is probably due to the influence of direct sun as the high percentage of cooling load occurs to large window area with insufficient overhang depth cases and the case without shading in winter solstice. The results, therefore, show that the large window area might not be a good solution both for daylighting and thermal comfort.

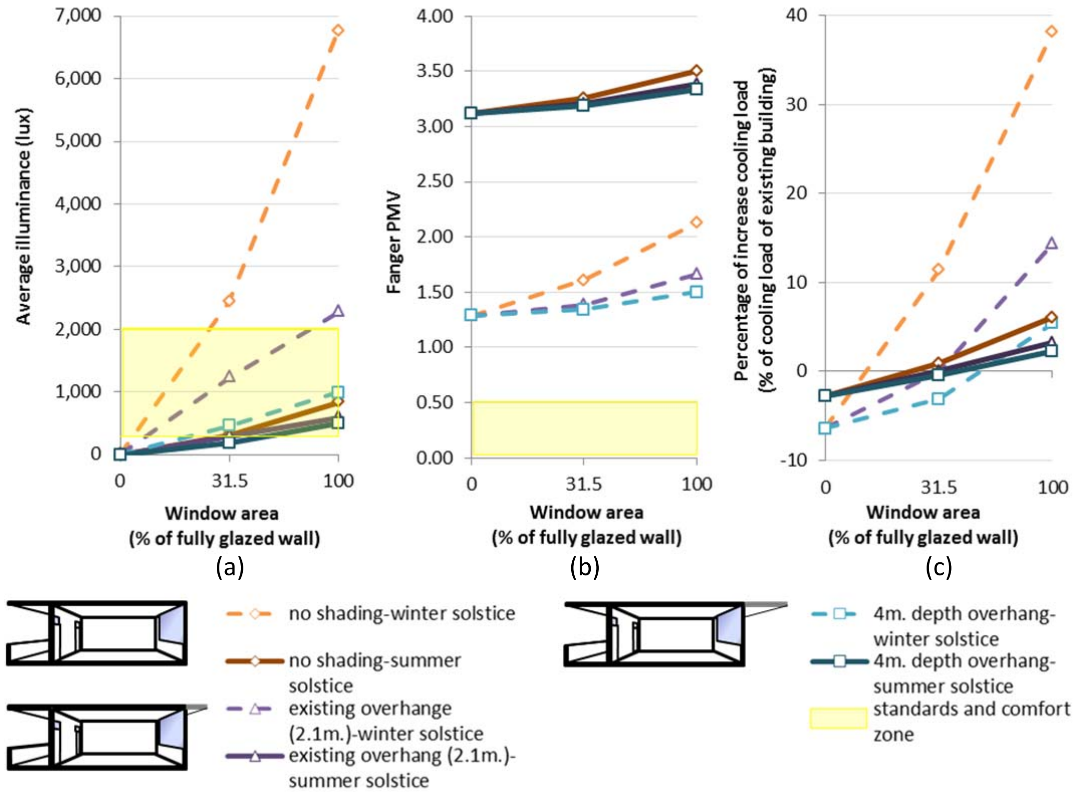


Fig.5. 7 Impact of window area and overhang depth on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

When the overhang depth cases were compared in Figure 5.7, it is more different illuminance, Fanger PMV and percentage of increase cooling load for the bigger window. There are much more differences in winter solstice than summer solstice. However, it is no significant difference in summer solstice. The no shading cases appear to provide too much illuminance and cooling load. The window areas that can make the illuminance meet the standards are approximately between 55.5-82.5% in all case, excluding the no shading cases. In terms of thermal shown in Figure 5.7(b) and (c), less overhang brings about more Fanger PMV and increased cooling load. The Fanger PMV of all cases in summer are much higher than in winter. The cases in the winter actually consumed more cooling energy as well but when comparing to the existing feature, it is less increasing cooling load than summer.

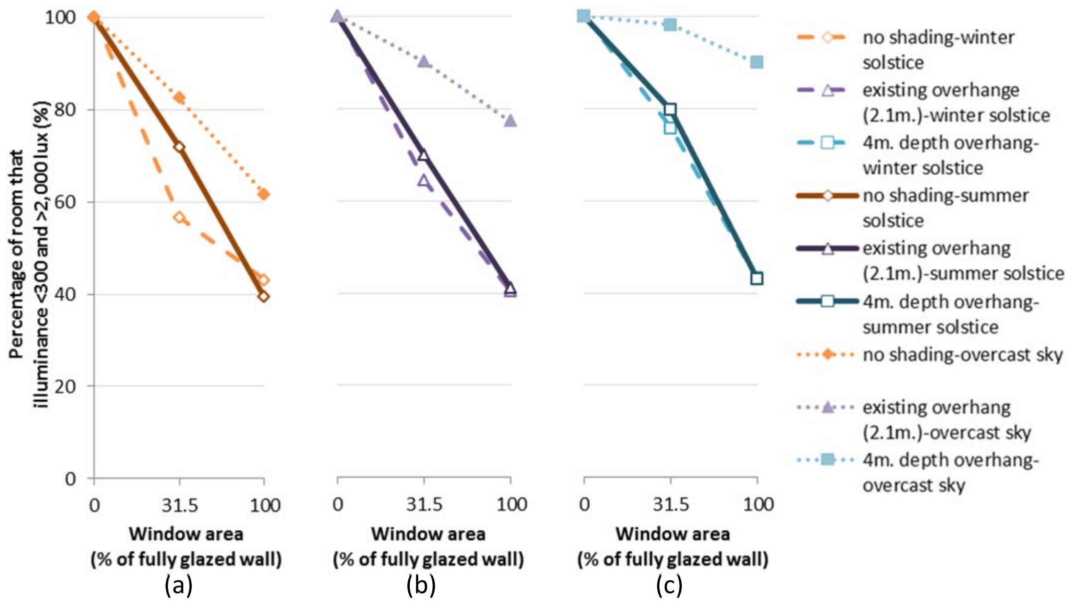


Fig.5. 8 Impact of window area on percentage of room the illuminance does not meet the standards for (a) on shading cases, (b) existing overhang cases and (c) four metre depth overhang cases.

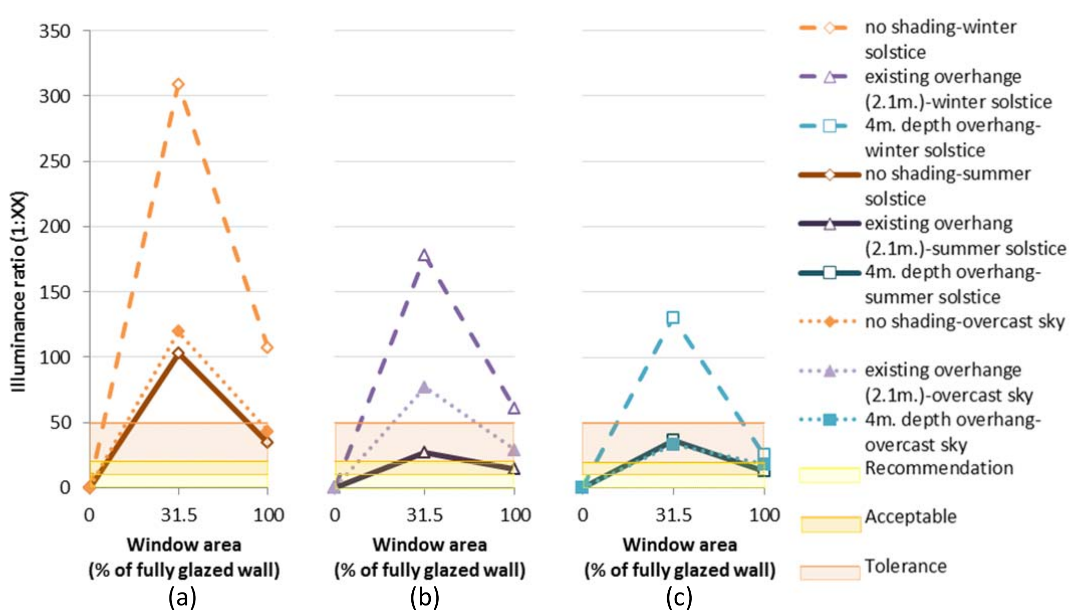


Fig.5. 9 Impact of window area on illuminance ratio for (a) on shading cases, (b) existing overhang cases and (c) four metre depth overhang cases.

Figure 5.8 shows that an increase of window area results in a bigger percentage of the room's illuminance meeting the standards. The reduction rates of the improper value in winter solstice approximates to summer solstice while lower than the rates in overcast sky. This also reveals the impact of direct sun on improving daylight levels. For illuminance ratios shown in Figure 5.9, it appears that the least and the most window areas are much more acceptable than existing window particularly for the cases without overhang or in winter solstice. In this case, the results of less window area could not be generalised as a practical solution because the ratios come from division of less illuminance.by very less illuminance. However, the existing window area might not be totally unacceptable due to the fact that there are some periods for the existing overhang and four metre depth overhang cases that the ratios are tolerable.

The results imply that the existing window area cases appear not acceptable in providing a low proportion of acceptable daylight quantity to the room. Additionally, their contrast ratios are either in tolerance or excessive high. The recommended window area could be about 55.5-82.5% with at least about two metre depth overhang since it provides required illuminance while the Fanger PMV and cooling load appear not too much high. However, the results of the percentage of the room that illuminance does not meet the standards and illuminance ratio point out that the fully glazed wall cases probably are more practical. The solution actually needs to be combined with the adequate shading as shown in Figure 5.7(a) and (c) that the illuminance and cooling load of fully glazed wall with existing overhang are too high while it is much lower for the case with four metre depth overhang. The lowest overhang depth that can reduce the impact of direct sun most effectively is between 2.1 and four metres. More exact depth of overhang should be indicated for more practical suggestions.

5.5 Overhang depth

Many cases of overhang depth were studied. There is no overhang, existing overhang (2.1 metre depth, four and six metre depth for base case window area and fully glazed wall. Additionally, seven and eight metre depth for fully glazed wall were added for fully glazed wall. In order to make them comparable, the depths were transferred to be percentage of optimised shading device for each window area cases. There are 0%, 35%, 66.67% and 100% for the base case window and 0%, 26.25%, 50%, 75%, 87.5% and 100% for fully glazed wall respectively. Expectedly, the less overhang depth the more illuminance and cooling load. Figure 5.10 shows relationships of overhang depth and the three indicators for base case window compared to fully glazed wall cases. The less overhang depth might provide adequate illuminance in summer solstice but it rather cause excessive high illuminance in winter solstice (Figure 5.10(a)). It also causes more heat gain resulting in substantial high cooling load particularly in winter solstice (shown in Figure 5.10(b) and (c)). Concordantly with the result of window area case, one of difficulties of applying overhang possibly is the influence of the direct sun.

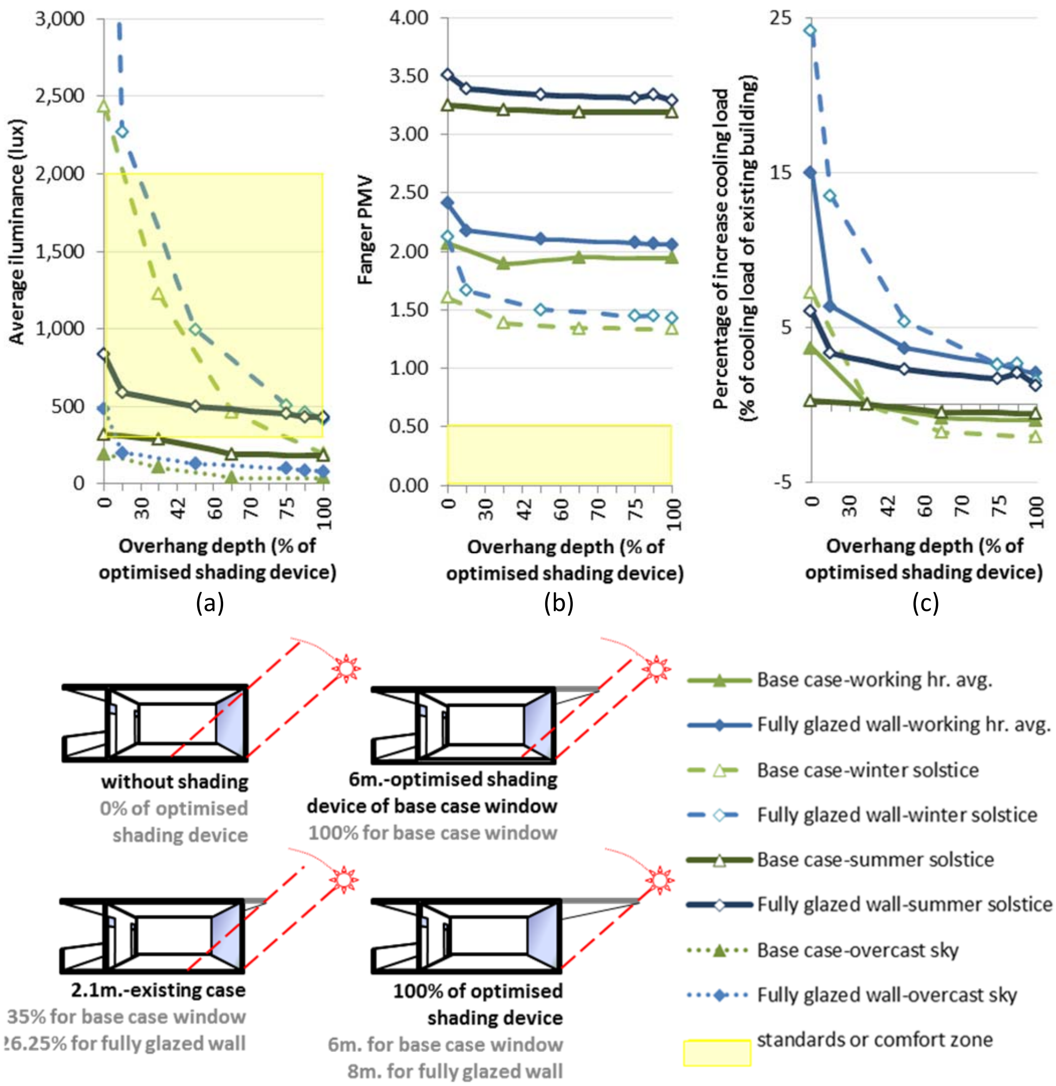
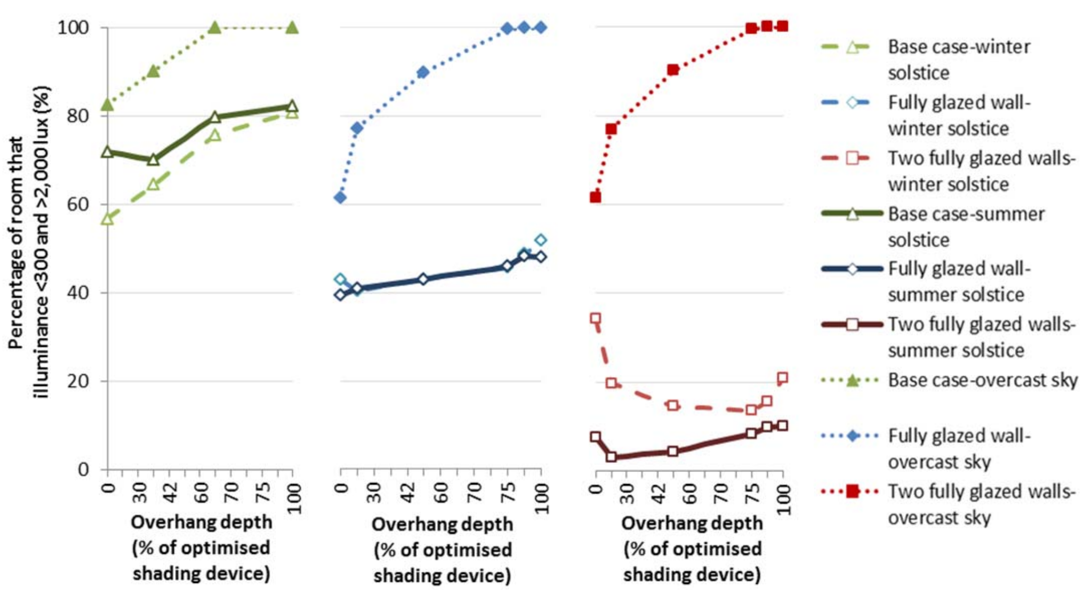


Fig.5. 10 Impact of overhang depth and different weather of winter and summer on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

For the fully glazed wall cases, it is obvious in Figure 5.10 that average illuminance meets the standards for all overhang depths in the summer solstice while in the solstice there are the depths more than about 30% (about 2.4 metre depth) that illuminances are above the standards. For the base case, between about 15% and 30% (approximately 0.9 and 1.8 metre depth) of overhang depth cases are in the standards for both winter and summer solstice. In overcast sky condition, most of daylight levels are lower than standard. For thermal comfort, the cases without overhang are the only case that provides significant high Fanger PMV scale while the other cases are almost constant (see Figure 5.10(b)). For the exiting window case, applying 66.67-100% depth of overhang (four and six metre depth) can reduce cooling load maximally about 2% in winter. However, there is no significant difference between the two cases. About 6-25% of cooling load can be increased for fully glazed wall when it is no shaded. The increasing rate greatly reduced when shading devices were combined. It is from 50% to 100% of overhang depth for fully glazed wall (four to eight metre depth) that the percentages of increasing cooling load lend to be no change. The increasing rates in winter are higher than that in summer. The differences of the rates between winter and summer are substantial high in less depth cases and very little from 75% to 100% cases (Figure 5.10(c)).



(a) (b) (c)

Fig.5. 11 Impact of overhang depth on percentage of room the illuminance does not meet the standards for (a) existing window cases, (b) fully glazed wall cases and (c) two opposite fully glazed wall cases.

In terms of daylight distribution shown in Figure 5.11, although the less overhang depth tends to have more illumination level, the overhang depth appears to have less impact than window area. While changes of overhang depth can improve about 5-20% satisfied illuminances, it can be 20-70% for the changes of window area. Except the overcast sky cases that illuminances generally do not meet the standard, the fully glazed wall cases provide less than 50% of dissatisfied rate (Figure 5.11(b) and (c)).

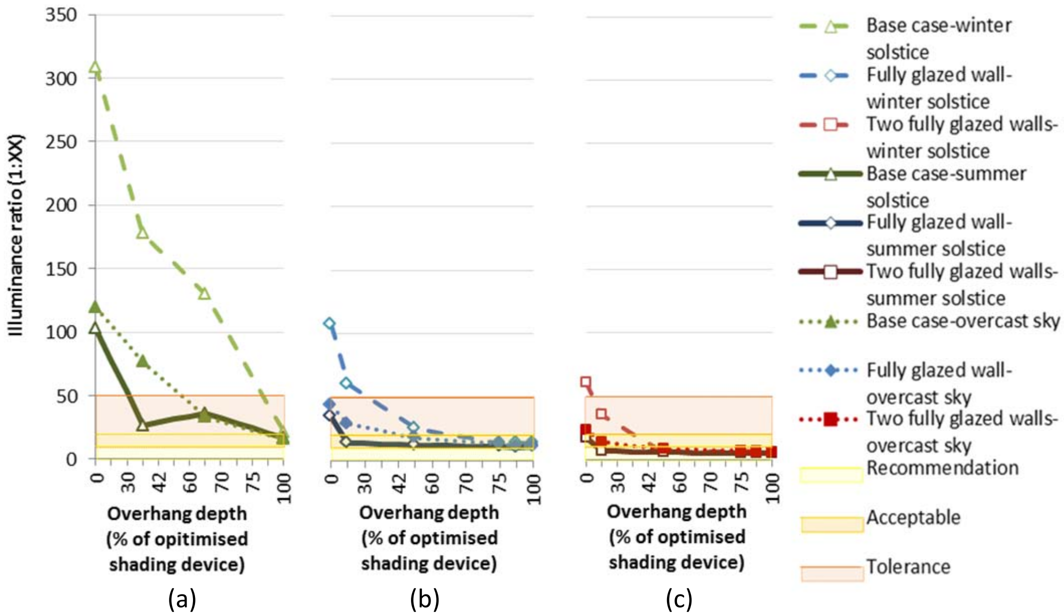


Fig.5. 12 Impact of overhang depth on illuminance ratio for (a) existing window cases, (b) fully glazed wall cases and (c) two opposite fully glazed wall cases.

For illuminance ratio, less overhang depth generally provides more ratio. The ratio can be substantial high when direct sun influence such as in winter solstice and the cases without shading (see Figure 5.12). Illuminance ratios of existing window are unacceptable mostly in overcast sky and winter clear sky. About lower than 30% of optimized device for existing window (about 1.8 metre depth) that the ratio was always less than tolerance level. For fully glazed wall cases, the ratio meet standards excluding less than about 30% (about 2.4 metre depth) and 10%(about 0.8 metre depth) of optimized device for fully case wall and two opposite fully glazed walls respectively. Most cases of fully glazed wall meet acceptable level while that of two opposite fully glazed walls meet recommended level.

Consequently, for existing window the depth about 30% of optimized overhang (about 1.8 metre depth) appears to be optimised depth for average illuminance, thermal comfort rate and illuminance ratio. It is only up to 3% of cooling load can be increase at this depth. However, it is note that minority of room that illuminance meet standard occurred in all cases of overhang depth for existing window. It is more flexible in fully glazed cases. The depth from 50% to 100% (four to eight metre depth) provided sufficient daylight, acceptable illuminance ratio, the least thermal comfort rate and cooling load in general. Due to the fact that there is not significant difference between the depths from 50% to 100%, the depth of 50% can be the best solution for fully glazed wall cases.

5.6 Impact of the opposite side aperture

As one of window type which has been selected to be the maximum feasibility of window area of typical classroom, the two opposite fully glazed wall cases were examined and compared. On its own, the corridor side windows appear to have less impact to illumination level and human comfort. The comparisons of corridor-side window cases: no window, the small windows above the doors and the fully glazed wall, show just a little more illuminance of the fully glazed case than other cases (see Figure 5.13(a)). For Fanger PMV (shown in Figure 5.13(b)), fully glaze wall cases are not much different to other cases although window areas are much larger. It might due to the fact that the corridor is about four metre large then the same size of the upper floor be able to be counted as a deep overhang which may dramatically reduce influence of solar radiation. However, the result in Figure 5.13(c) shows that cooling load proportion of fully glazed wall cases are about 5-9% higher than the other cases. Another issue is the case of fully glazed wall is the only case that increase cooling load for about 2.5-4% of existing façade. It can be claimed that the opposite side window has less impact on both amounts of daylight than heat transfer.

The results agree when it was combined to the main window. As it shown in Figure 5.14(a), average illuminance of two opposite fully glazed wall cases is very close to that of single fully glazed wall cases whereas they are much different to base case. It is also not much different for Fanger PMV (Figure 5.14(b)). The differences of the base cases to the fully glazed wall cases approximate to the differences of the single fully glazed wall to the two opposite fully glazed wall cases. Interestingly, the differences of single to two fully glazed wall cases are significant for cooling load. The more overhang depth the more increase cooling load. With less influence of direct sun, the results reveal the hidden negative effect of the large window area that might provide more heat gain causing high percentage of increase cooling load.

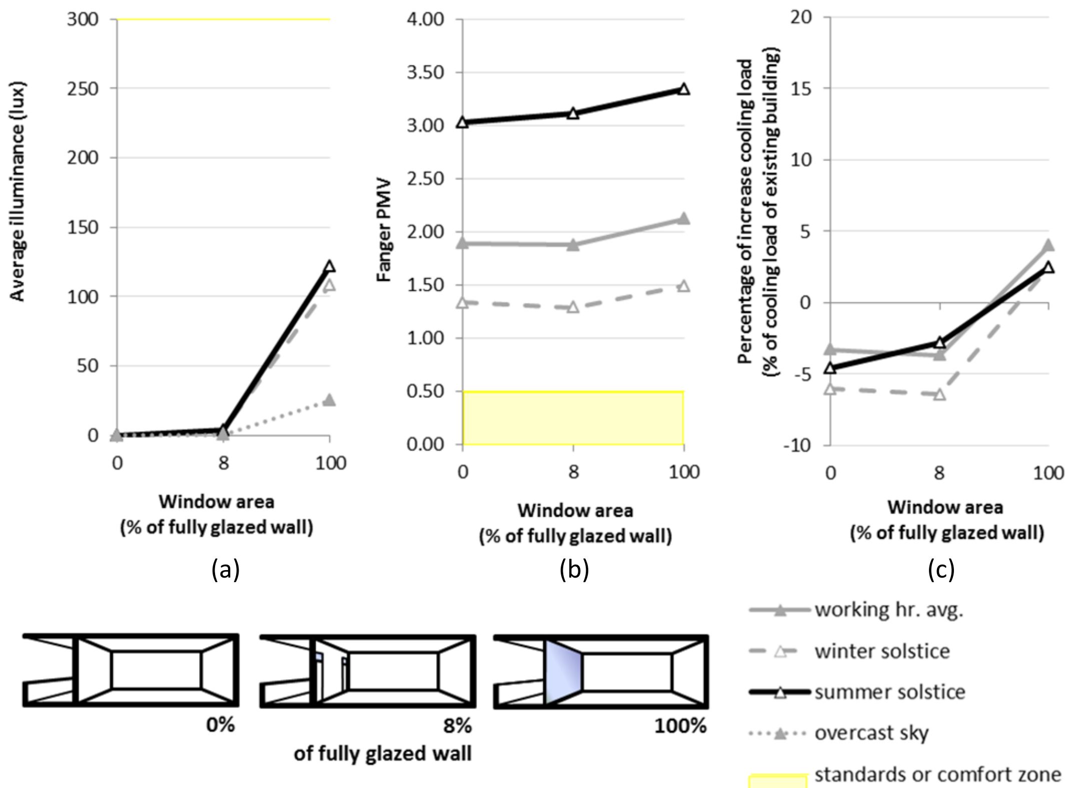


Fig.5. 13 Impact of opposite side window on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

However, advantages of combining the opposite side window that rather just increase the percentage of proper illumination levels, it can also reduce the illuminance ratio to be at least tolerance rates. In other words, too much brightness contrast issues which are very general for single sidelighting of typical classrooms possibly can be solved by applying window which connected to the corridor. As shown in Figure 5.11(c), the percentage of room that illuminance does not meet standard are very low for two opposite fully glazed wall cases. The pattern of the graph are different to other window types, more steady and the lowest is for the cases with between 26.25-75% depths of overhang instead of no shading cases. The illuminance ratios in Figure 5.12(c) also confirm efficiency of this additional window. Majority of them is lower than tolerance level. The possible solutions of overhang depth for this window type should be more than 10% (0.8 metre depth) for tolerance level, 35% (2.8 metre depth) to be acceptable and 50% (four metre depth) for the recommendation ratio. Furthermore, more than about 30% (1.8 metre depth) can lessen the average illuminance in winter solstice into the standards (see Figure 5.14(a)).

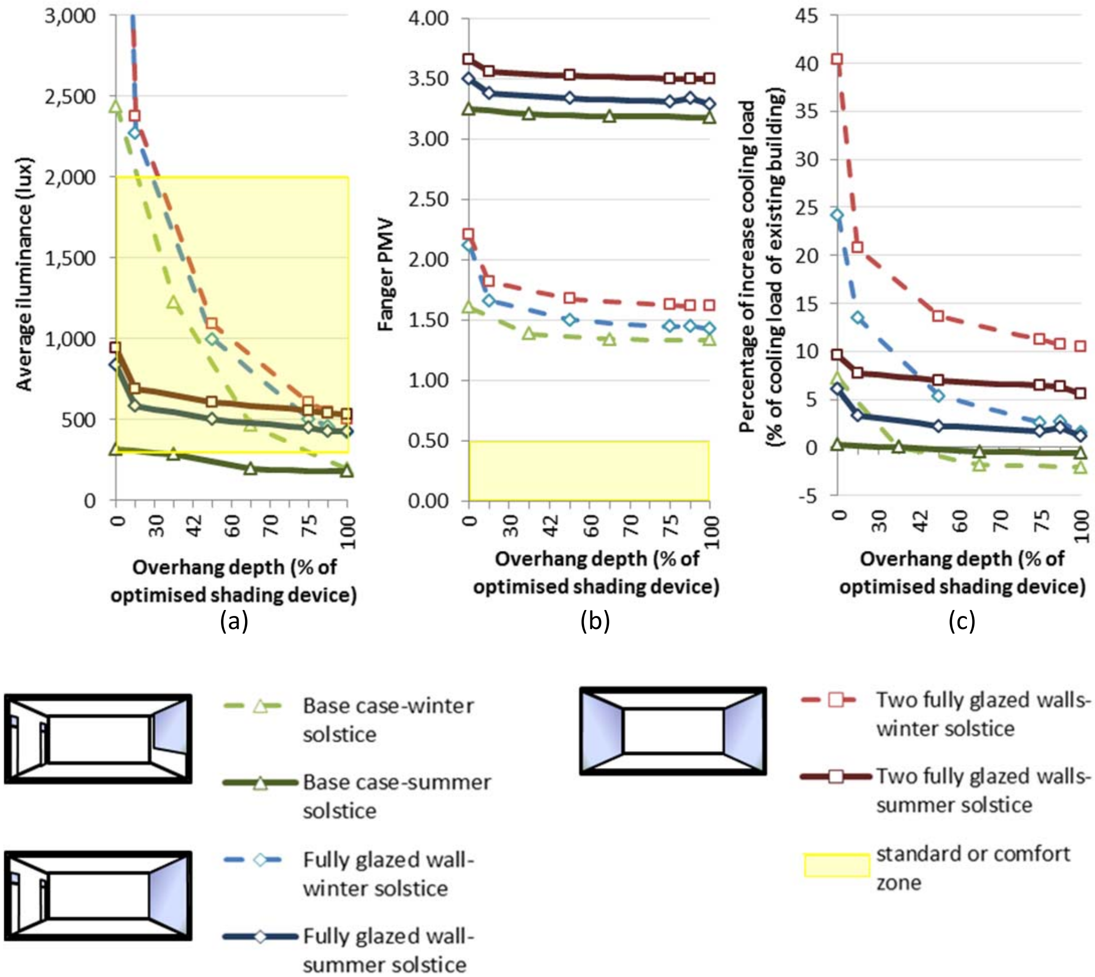


Fig.5. 14 Impact of overhang depth and window type on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

It is obvious like other cases that more overhang depth provides less proportion of an increased cooling load. However, the results introduce a conflict between daylighting and cooling load when using large window area for both side of classroom facade. According to Figure 5.14(c), while enlarging window area increases about 2-20% of cooling load from base case, the additional fully glaze window provides about 10-15% more. It is about 10-35% in total that cooling load increases from the base case. However, the recommended shading depths of fully glazed wall: 50% of opimised device; provides the less increasing cooling load. The impact of thermal aspect also shows in Figure 5.14(b). It is not much difference of Fanger PMV rates between the two opposite fully glazed case and other cases. The maximum is about five PMV scale warmer than the base case. All in all, although the result of cooling load tended to be unpleasant, the advantage of additional fully glazed wall in term of daylight level sufficiency and uniformity reveals that the window addition is one of the most effective strategies.

5.7 Window orientation

Theoretically, window orientation is known as one of the most influential parameters on daylighting as the effects of sun geometry. Since the previous parameters were simulated, significant differences of sun geometry was found critical in the cases that direct sun influenced the façade. The window orientation parameter, therefore, was examined integrated with the effect of direct sunlight in the room and depths of overhang related to its orientation. The focused window orientations in this study are south, north, west, east and southwest which is the orientation of the case study.

1) Impact of direct sun on orientation

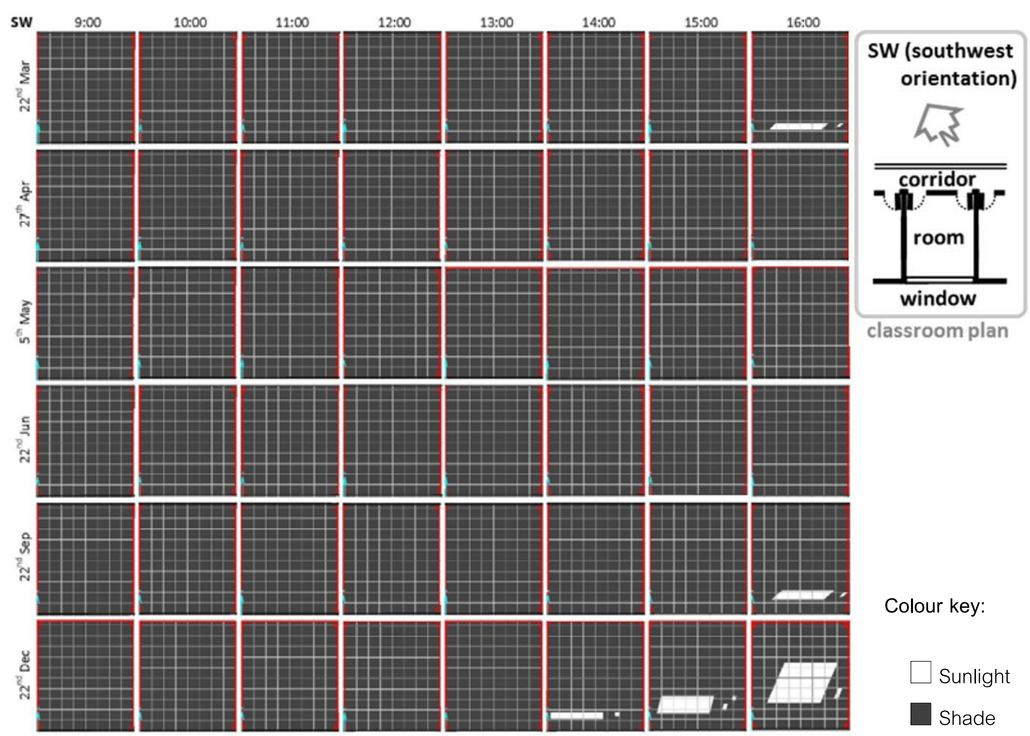
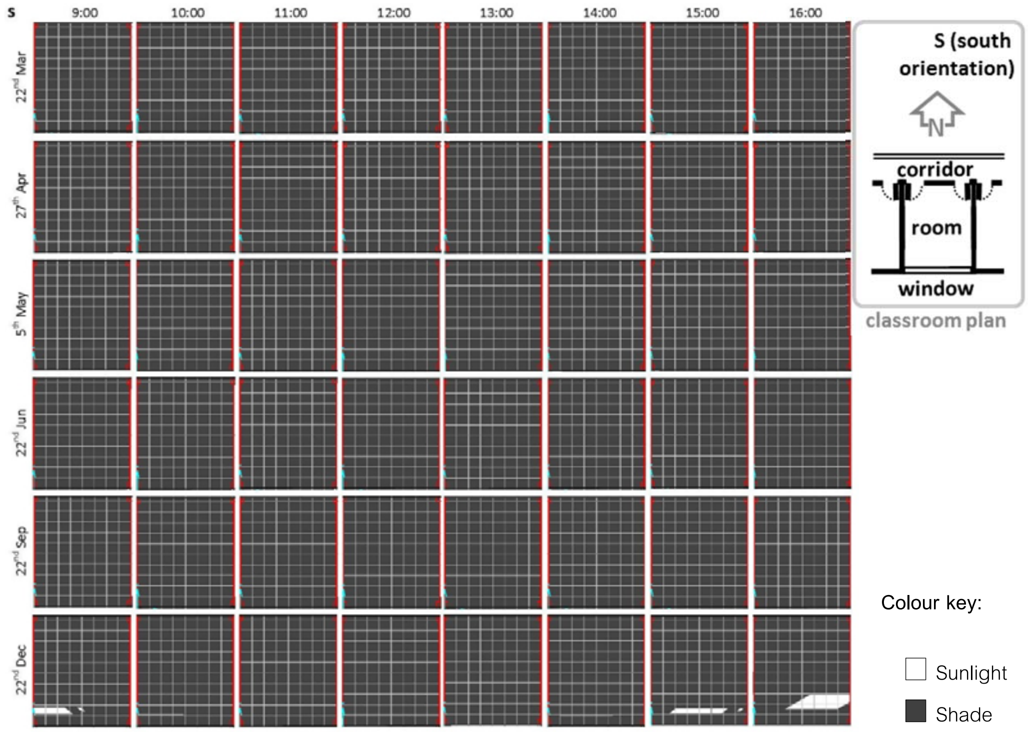
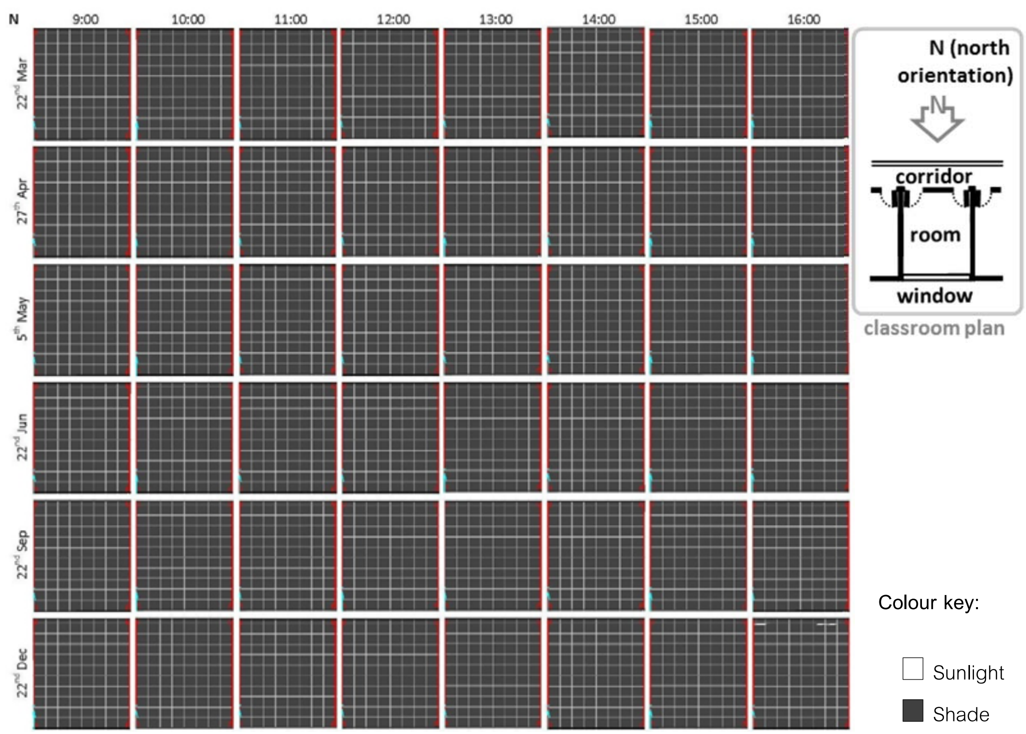


Fig.5. 15 Direct sunlight pattern on the floor of southwest orientation classroom with 2.1 metre depth overhang in six specific dates during working hour.

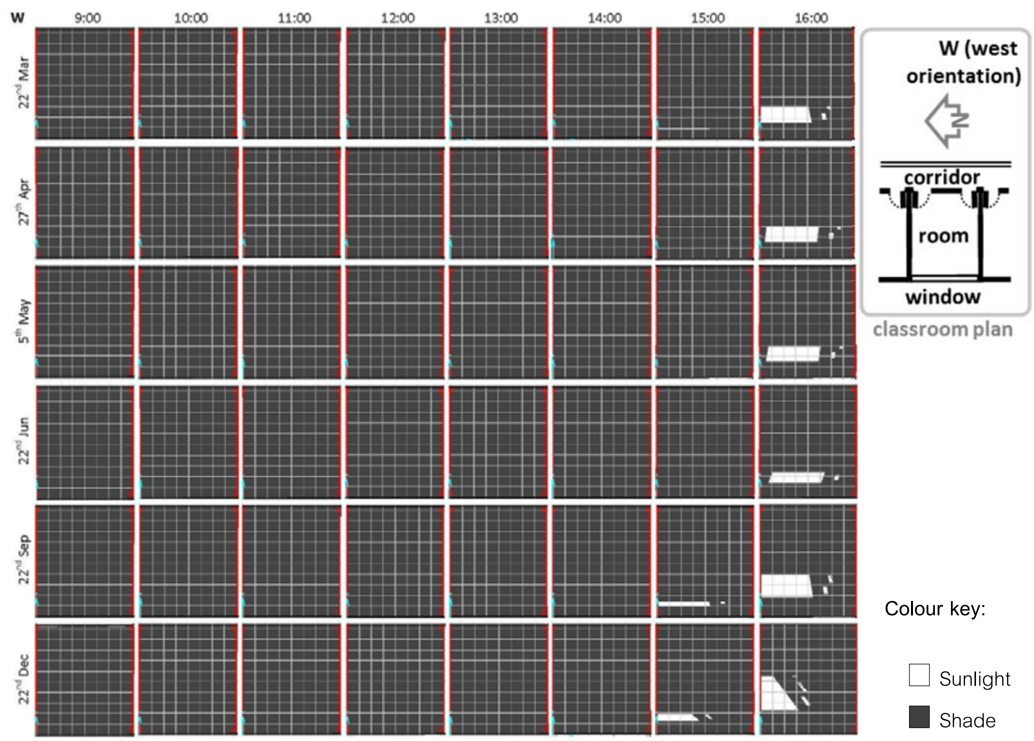


(a)

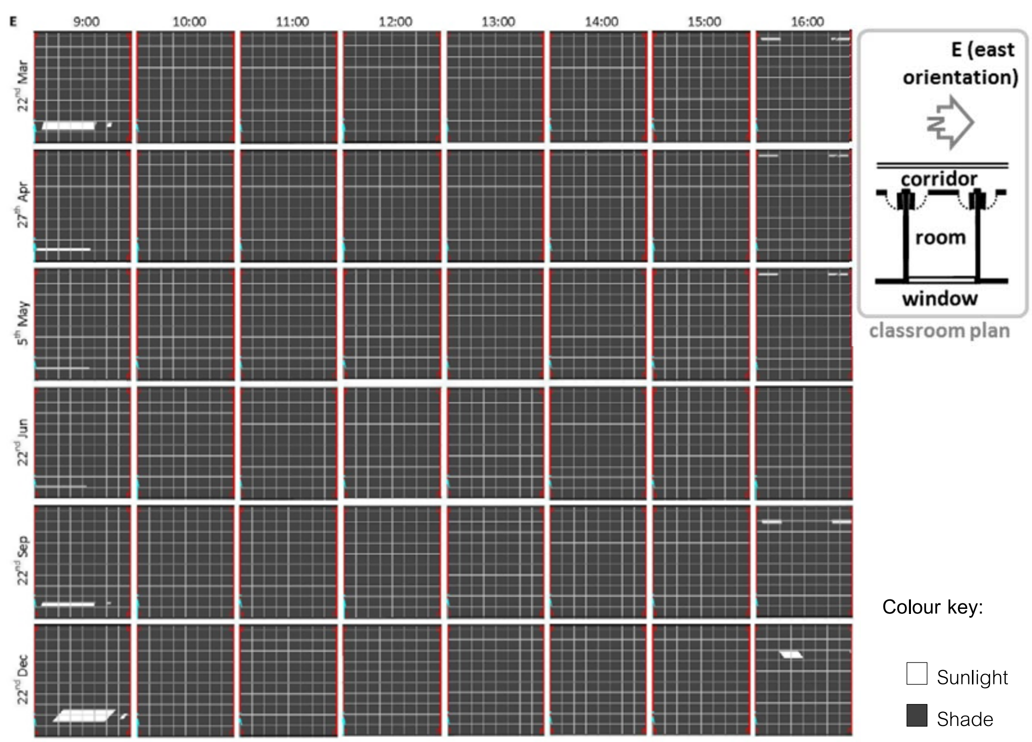


(b)

Fig.5. 16 Direct sunlight pattern on the floor of classroom with 2.1 metre depth overhang in six specific dates during working hour: (a) south orientation and (b) north orientation



(a)



(b)

Fig.5. 17 Direct sunlight pattern on the floor of classroom with 2.1 metre depth overhang in six specific dates during working hour: (a) west orientation and (b) east orientation

An effect of sun geometry on the facade appears to have high impact mostly for illumination especially when direct sunlight was allowed. For southwest orientation which is the base case, the predictions generally overwhelmed because the sun altitude is generally low, in winter solstice or at 4PM for example. In this part, sunlight penetration is interested because it has been assumed that have high impact on both daylighting and thermal aspect. Differences of penetration pattern can occur when time and season change. During working hours (9AM-4PM), six specific dates: equinoxes (22^{nd} of March and September), the dates that the sun is vertically overhead (27^{th} of April and 5^{th} of May), summer solstice (22^{nd} of Jun) and winter solstice (22^{nd} of December) were studied using Shadow display analyses of Ecotect.

For the existing orientation shown in Figure 5.15, direct sunlight was allowed into the room the most in winter solstice from 2PM to 4PM. It also affected on 4PM of equinoxes. The most effect was in winter solstice which affected about 20% in the middle area of the room. The direct sunbeams effect only on winter solstice for south and north oriented classrooms. When the window faced to north in Figure 5.16 (b), it was very small areas of sunlight transferring through windows above the doors at 4PM. The areas were larger for south orientation which occurred at 9AM and between 3PM and 4PM from the window (see Figure 5.16(a)). The largest area at 4PM was much smaller than that in the southwest case.

The patterns are different for west and east orientations (Figure 5.17). The west orientation room shown in Figure 5.17(a) appears to be influenced by the sun significantly at 4PM for a whole year and at 3PM during winter period (from September to March equinoxes). The sunlight from the window had little effect on the east orientated room at 9AM throughout the year while almost all of the year at 4PM from the top window of the doors. Expectedly, when compared to distribution predictions, the effect of direct sun also leads to overwhelming illuminance which probably much more than the standards (see Figure 5.18-5.22).

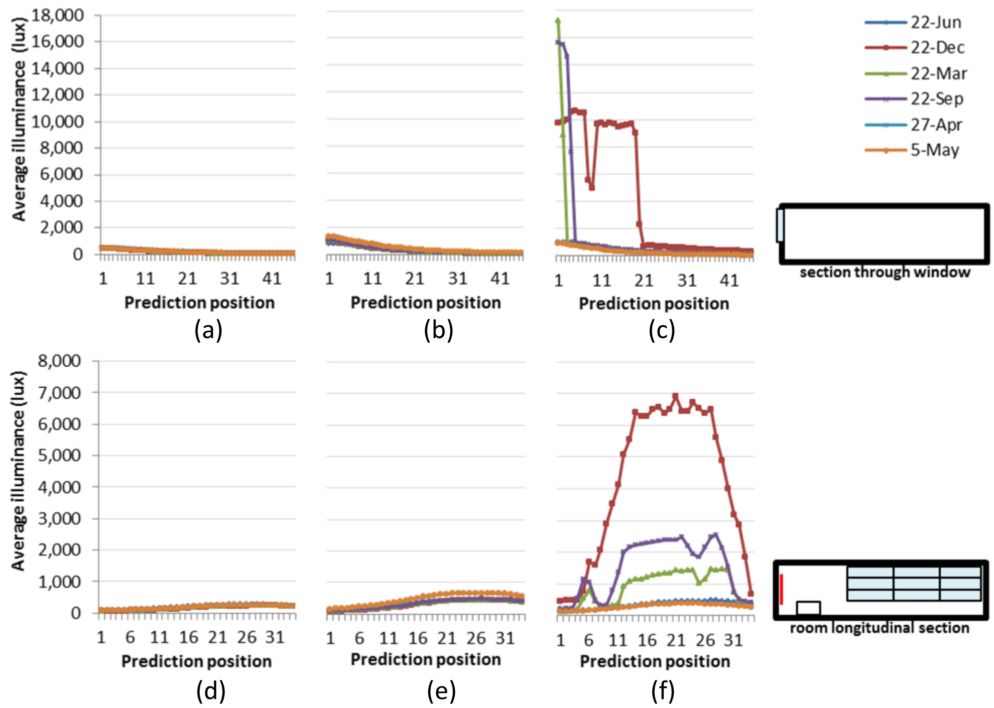


Fig.5. 18 Average illuminance of the southeast orientation classroom for transversal and longitudinal section at 9:00((a)and(b)), 12:00((b)and(e)) and 16:00((c)and(f)).

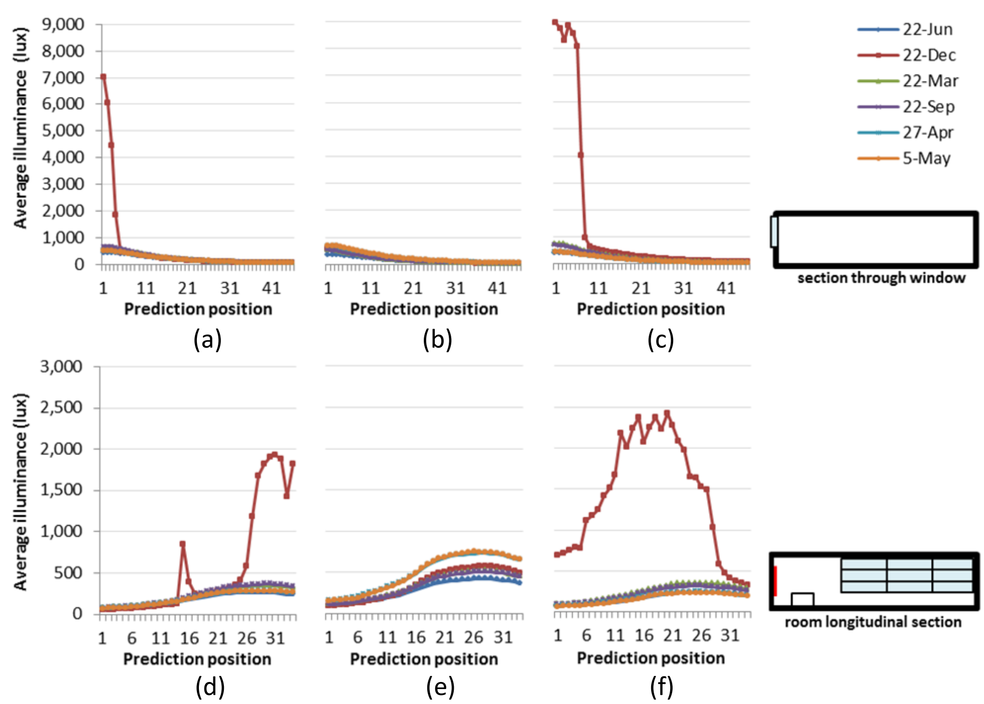


Fig.5. 19 Average illuminance of the south orientation classroom for transversal and longitudinal section at 9:00((a)and(b)), 12:00((b)and(e)) and 16:00((c)and(f)).

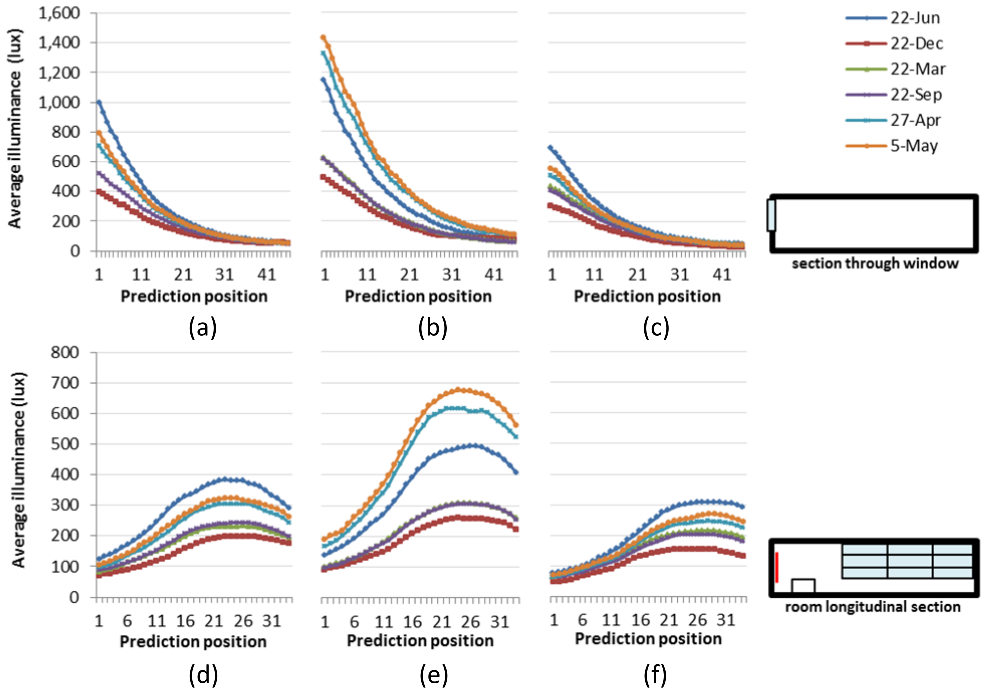


Fig.5. 20 Average illuminance of the north orientation classroom for transversal and longitudinal section at 9:00((a)and(b)), 12:00((b)and(e)) and 16:00((c)and(f)).

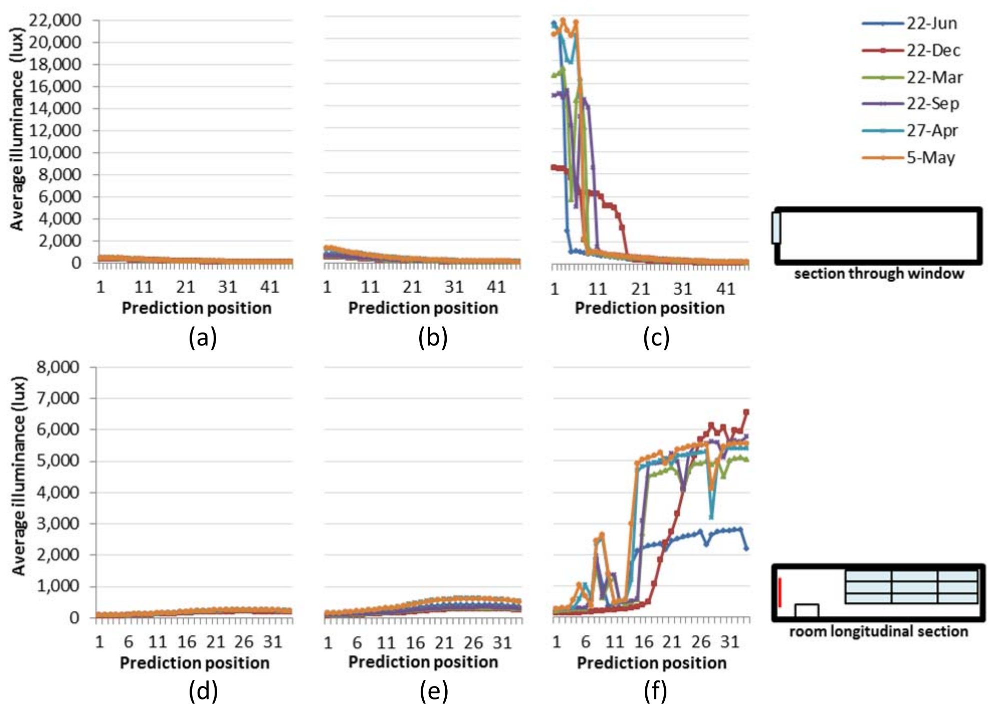


Fig.5. 21 Average illuminance of the west orientation classroom for transversal and longitudinal section at 9:00((a)and(b)), 12:00((b)and(e)) and 16:00((c)and(f)).

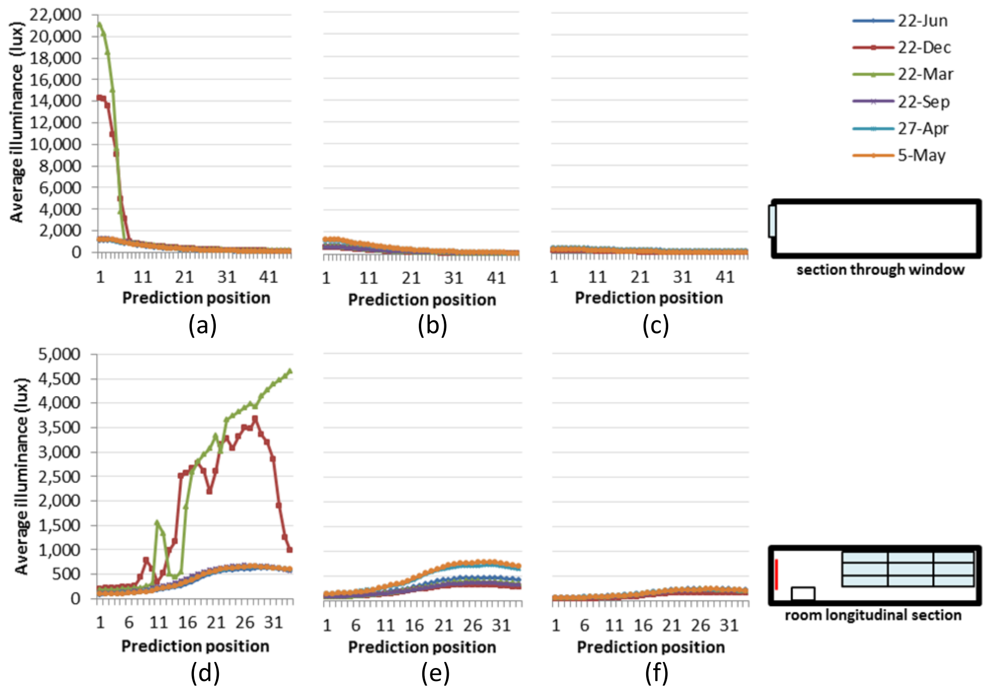


Fig.5. 22 Average illuminance of the east orientation classroom for transversal and longitudinal section at 9:00((a)and(b)), 12:00((b)and(e)) and 16:00((c)and(f)).

The more area of the room that incident direct sun light affect is not the more illumination level. According to Figure 5.21(c) and 5.22(a), the maximum average illuminance through window which are approximately 21,000 lux occur at 4 PM on 27th April, 5th May and 22nd June in a west orientation and 9AM on 22nd March in an east orientation which the areas are affected by direct sun are not the largest. The largest area is at 4PM on 22nd of December in the southwest orientation (compare Figure 5.15 to 5.17 which is the maximum illuminance cases). The result reveals that when direct sun beam affect the room in large area it might be less intensity of daylight than that in smaller areas. Basically, the larger area causes by the lower position of the sun. Although it is not the maximum, the largest area rather brings about depth of excessive high illuminance into the room (shown in Figure 5.18(c) and 5.21(c)). Higher intensity of direct sun which influence the room by high angle sun can be displaced effortlessly using shading device while the direct sun from low angle sun might not necessary to be fully shade as it has lower intensity and the great depth of shading device is needed for completely protecting.

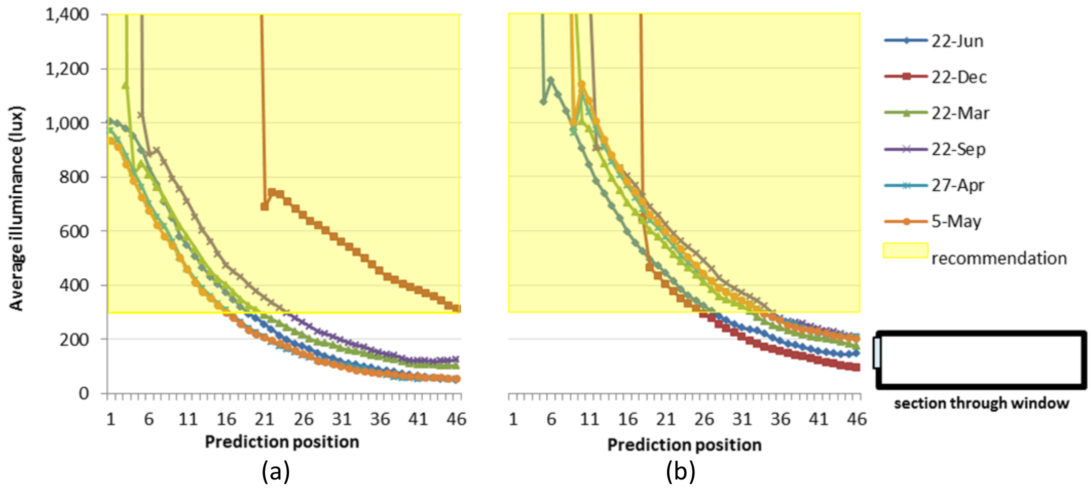


Fig.5. 23 Average illuminance in transversal section at 16:00 for: (a) southwest window orientation (the same graph as Fig.15(c)) and (b) west window orientation (the same graph as Fig.18(c))

From the affected area to the areas without effect of the direct sun, illuminance extremely reduces in all cases, Figure 5.23 for example. Usually, illuminance in unaffected areas gradually decreases by distance of window. The cases of 4PM in southwest and west orientations shown in Figure 5.23(a) and (b) respectively demonstrate the most possibility of daylight transfer that the illuminance meets the standard at the deepest positions of the room, at least one third for southeast facing and in the middle of the room for the west, comparing to other cases. It is more daylighting transfer for low sun angle conditions. Particularly at 4PM on 22nd December when the sun angle almost straight to the southwest window, the average illuminance met the standards in all positions (Figure 5.23(a)).

2) Application of five focused orientations in the existing building

When comparing the influence of direct sun from Figure 5.15-5.17 to predictions, it is concordant for average illuminance. Graphs in Figure 5.24(a) shows most effect during winter than summer particularly of southwest orientation which average illuminance reaches the peak on winter solstice as it was the longest effect of direct sun. However, the direct sunlight appears have less impact on thermal aspect as it is no significant different between five window orientation cases (shown in Figure 5.24(c) and (d)). This probably reveals that window orientation parameter has impact on illuminance while almost not significant for thermal aspect.

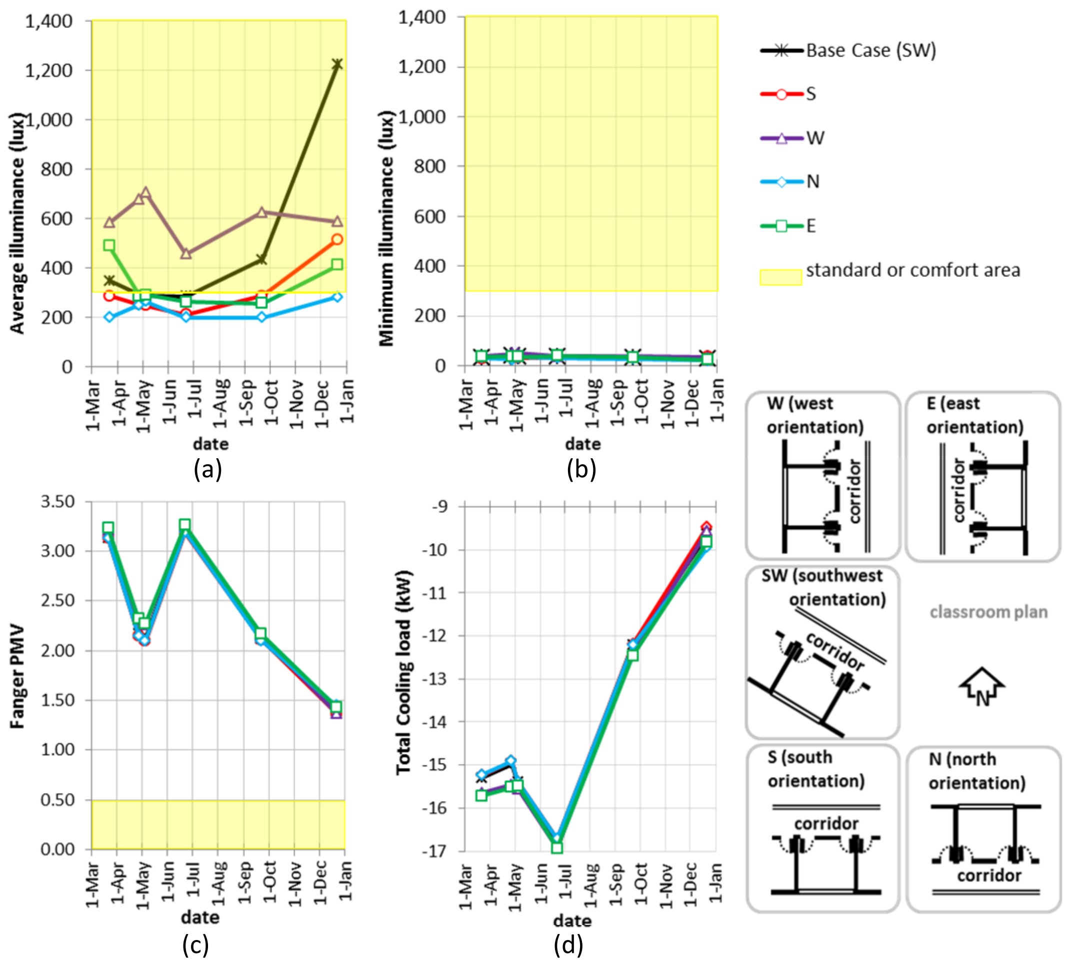


Fig.5. 24 Predictions of five window orientations in the six specific dates of the year: (a) average illuminance, (b) minimum illuminance, (c) Fanger PMV and (d) total cooling load.

In average (Figure 5.24 (a)), illuminance mostly meets the standards during winter. According to the average illuminance of room and time, southwest and west orientations appear meet the standards all year whereas the illuminance of north facing room is lower than the standards. Even though the graphs illustrate adequate illuminance in some orientations, it might be due to averages from high illumination level of direct sun. West orientation for example, the impact of direct sun in the afternoon throughout the year which was shown in Figure 5.17(a) probably cause the average illuminance in Figure 5.24(a) not only approximate in different dates but also higher than other orientation in average. The predictions of minimum illuminance in Figure 5.24(b) might also against the results of average illuminance. When the direct sun was not considered, there was no significant different illuminance between orientations as it was substantial low illumination level.

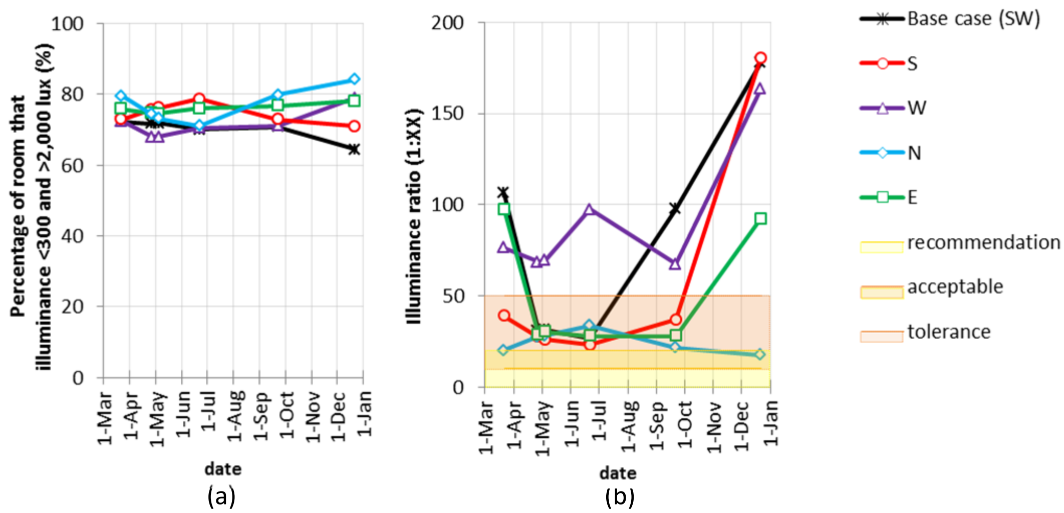


Fig.5. 25 Predictions of five window orientations in the six specific dates of the year: (a) percentage of room that illuminance does not meet the standards and (b) illuminance ratio

The negative effect of direct sun is also revealed in Figure 5.25(b) that the excessive high contrast ratio occurs mostly in the winter for all orientations which was influenced: Southwest, South, West and East. The ratios are much higher than tolerant especially for the west windows which obviously accept the sunlight in the afternoon during the entire year. On the other hand, north orientation which has no significant effect from direct sun bring about less ratios than tolerant level, moreover, the ratios meet acceptable level in winter when the sun influence south facing. As average, illuminances of the room with direct sunlight appear meet the standards (Figure 5.25 (a)) but the percentage of room that illuminance meet the standard shown in Figure 5.25(a) implies that it cannot be generalised. The graph shows that majority of room illuminance are not in the requirements in all orientations all year round. Obviously, north orientation gains very limited daylight in winter resulting in considerable high percentage of the room with the lower illuminances. The percentages are also high in other orientations but by the opposite aspect. For west orientation as the most obvious case, the highest percentage is also in the winter when influence of direct sunlight causing very high illumination level. This result reveals that direct sunlight also caused out-of-standard illuminance levels. This is significant as it is much higher than 2,000 lux which is a substantial high illuminance. However, room illuminance percentages of five orientations are more than 60% and not much different comparing to each other. The highest difference is about 20%.

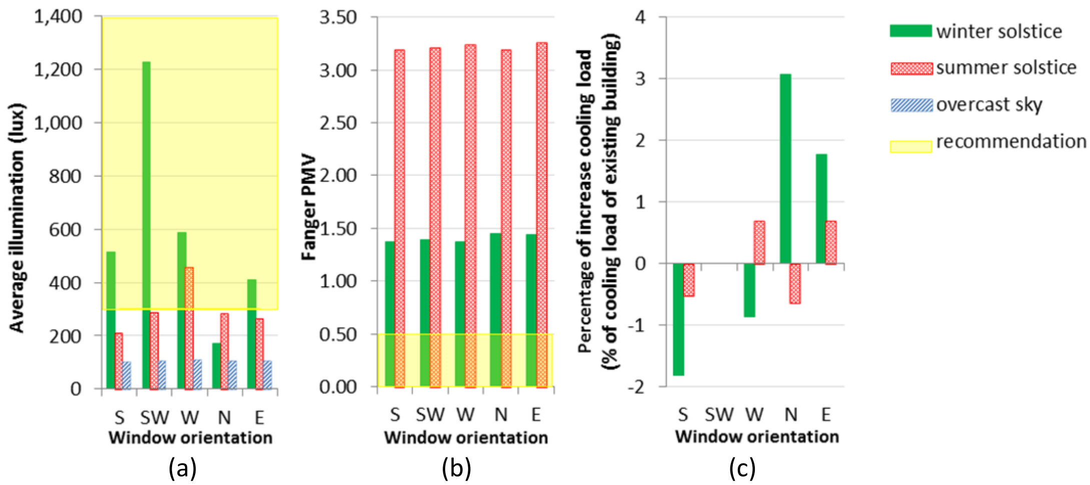


Fig.5. 26 Impact of window orientation and different weather of winter and summer on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load.

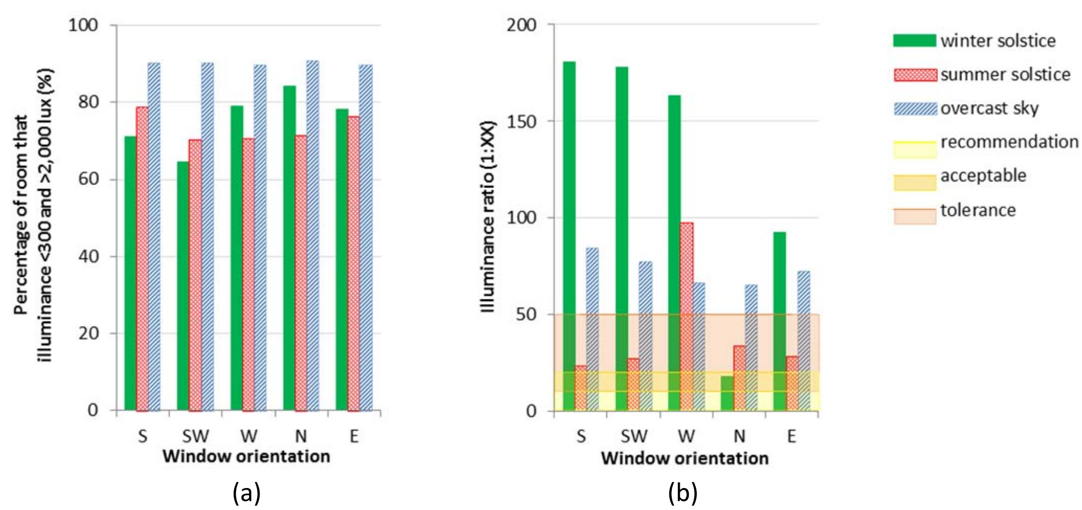


Fig.5. 27 Impact of window orientation and different weather of winter and summer on (a) percentage of room that illuminance does not meet the standards and (b) illuminance ratio

While there is no significant difference for percentage of optimum illuminance (Figure 5.27(a)) and thermal aspect (Figure 5.26(b) and(c)), the results appear to show reverse relationship between average illuminance and illuminance ratio. The predictions in north orientation and most of results during summer in other orientations result in acceptable or tolerant illuminance ratios (shown in Figure 5.27(b)) while their illumination levels are insufficient (see Figure 5.26(a)). On the contrary for west orientation and most of predictions in winter, illuminance ratios are unacceptable although average illuminances are in standards. It reveals that daylighting for existing window on its own might not adequate for all year in north orientation and for summer when the window facing southwest, south and east. Other daylighting strategies, for example window area increase and reflected solutions, and lighting integration should be included to these cases. Interestingly, according to the previous results, the issue of high illuminances and excessive high illuminance ratios in west orientation and other cases in winter which due to influence of direct sunlight possibly can be lessened by expanding overhang depth.

3) Relationship between overhang depth and window orientation

For optimal daylighting, the practical facade of previous simulations tended to be the fully glazed wall with partly shading in the period that the sun is almost perpendicular to the window plane. Since the optimum shading depths are different in each orientation, it is interesting to examine how different among them including what is the appropriate depth should be used. The predictions affirm that the effects of applying different shading depths are various in each window facing and different window area. The fully shading window cases, for instance, supposed to have similar results because the direct sun does not influence but the significant variations appear in total cooling load especially for fully glazed wall cases in the winter solstice (see Figure 5.29(c)). In terms of illuminance and Fanger PMV, there is generally no significant difference among shading optimization cases except the cases of north orientation in summer solstice which the most critical cases can be seen in Figure 5.31(a) and (b). It is higher illuminance and Fanger PMV than other orientations. The shading optimization function of Ecotect refuses necessity of shading for north orientation although the direct sun has little effect to the window in summer solstice. The cases without overhang, therefore, are also the optimise cases for this orientation.

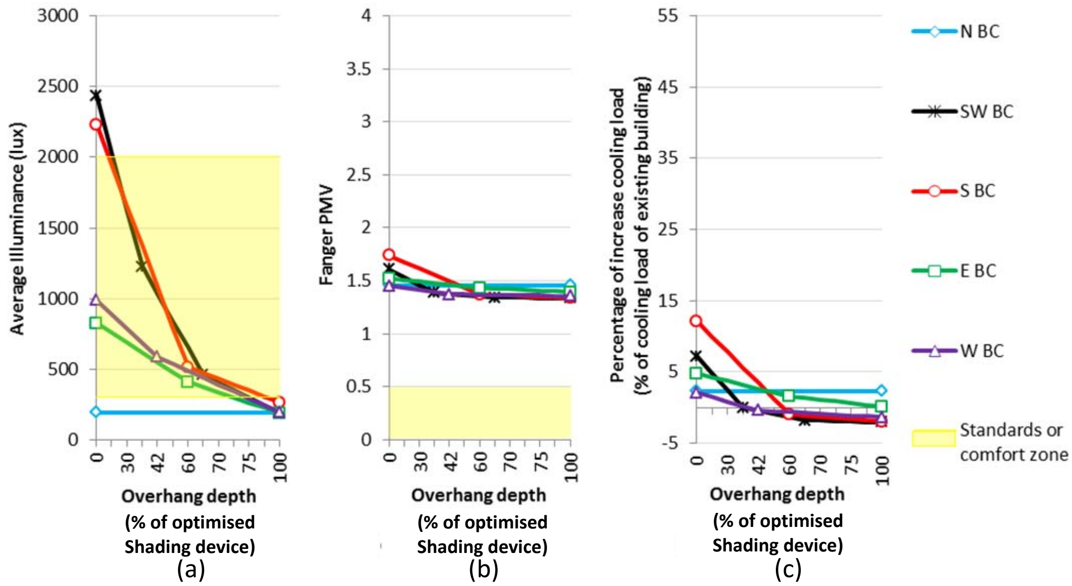


Fig.5. 28 Impact of window orientation and overhang depth on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load; for base case window in winter solstice.

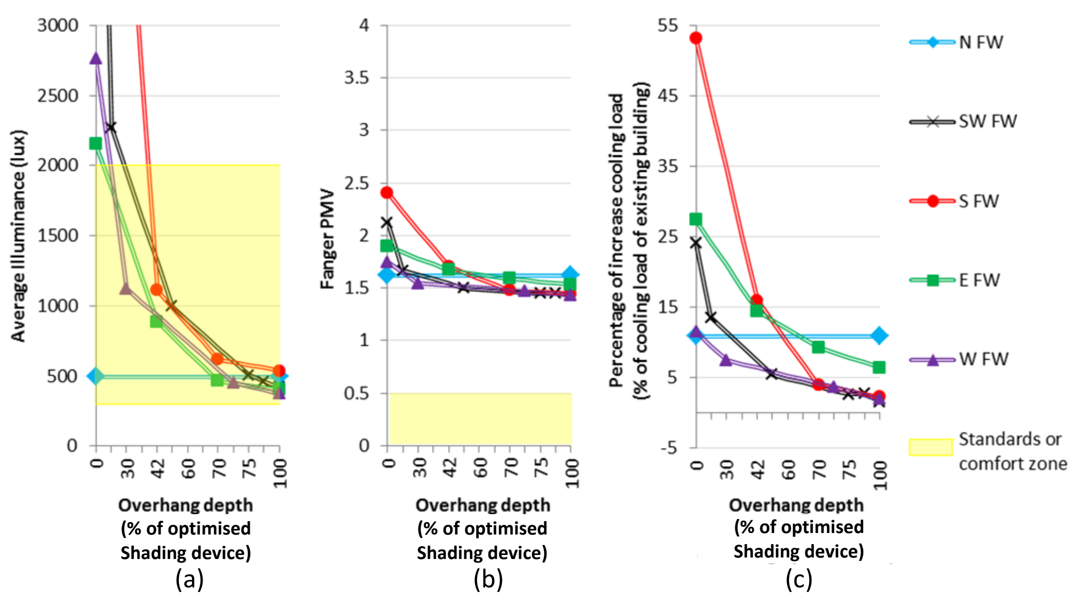


Fig.5. 29 Impact of window orientation and overhang depth on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load; for fully glazed wall in winter solstice.

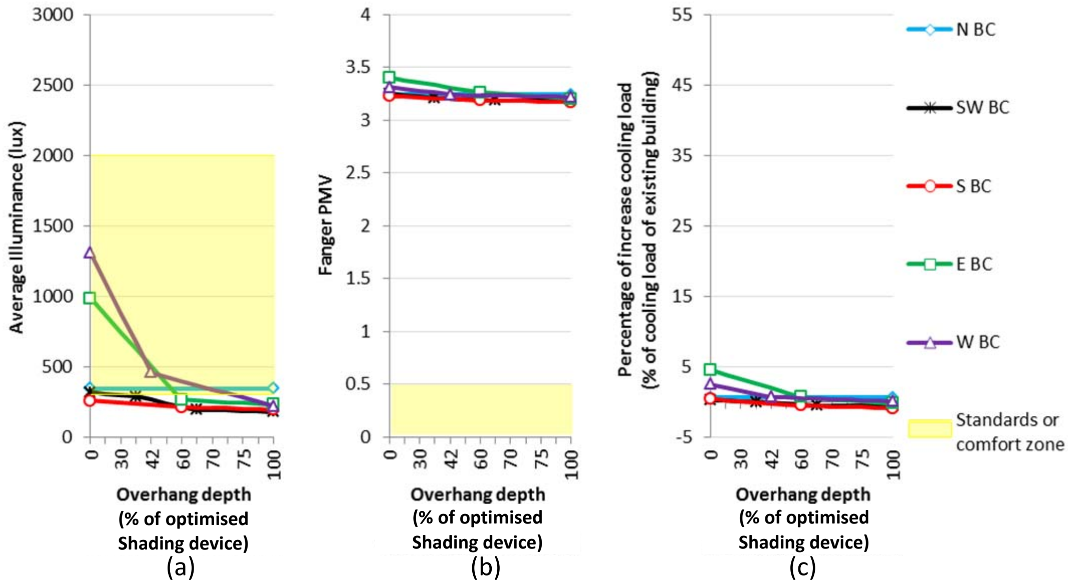


Fig.5. 30 Impact of window orientation and overhang depth on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load; for base case window in summer solstice.

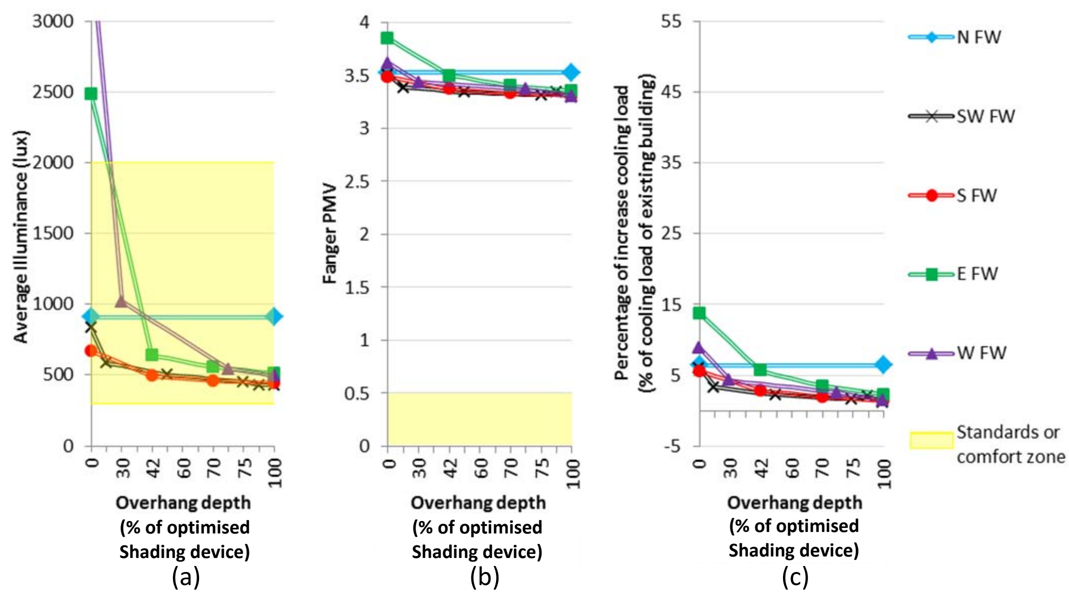


Fig.5. 31 Impact of window orientation and overhang depth on the three indicators: (a) average illuminance, (b) Fanger PMV and (c) total cooling load; for fully glazed wall in summer solstice.

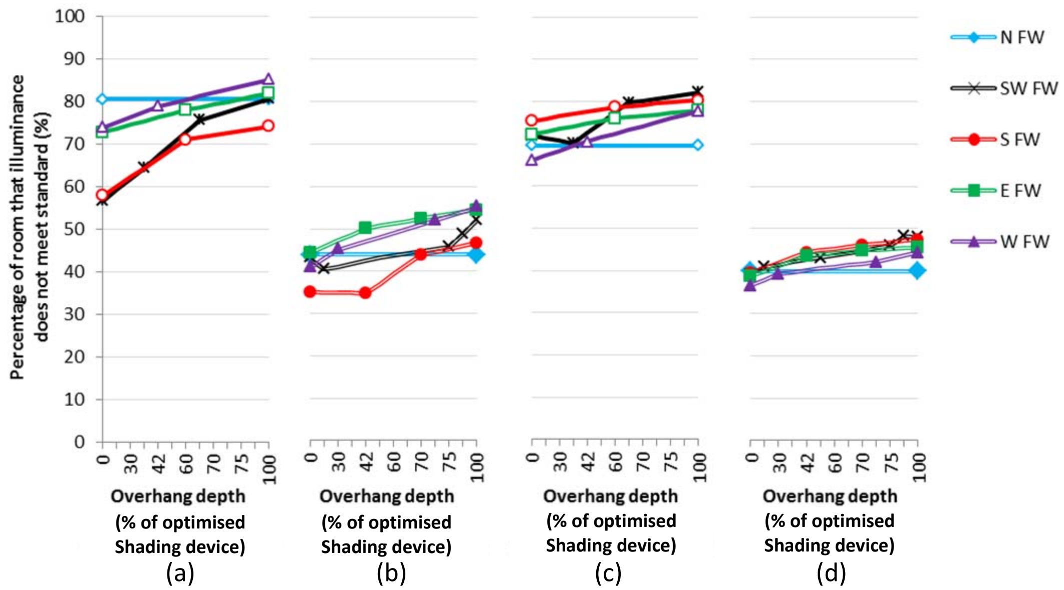


Fig.5. 32 Impact of window orientation and overhang depth on percentage of room that illuminance does not meet the standards for (a) base case window in winter solstice, (b) fully glazed wall in winter solstice, (c) base case window in summer solstice, and (d) fully glazed wall in summer solstice

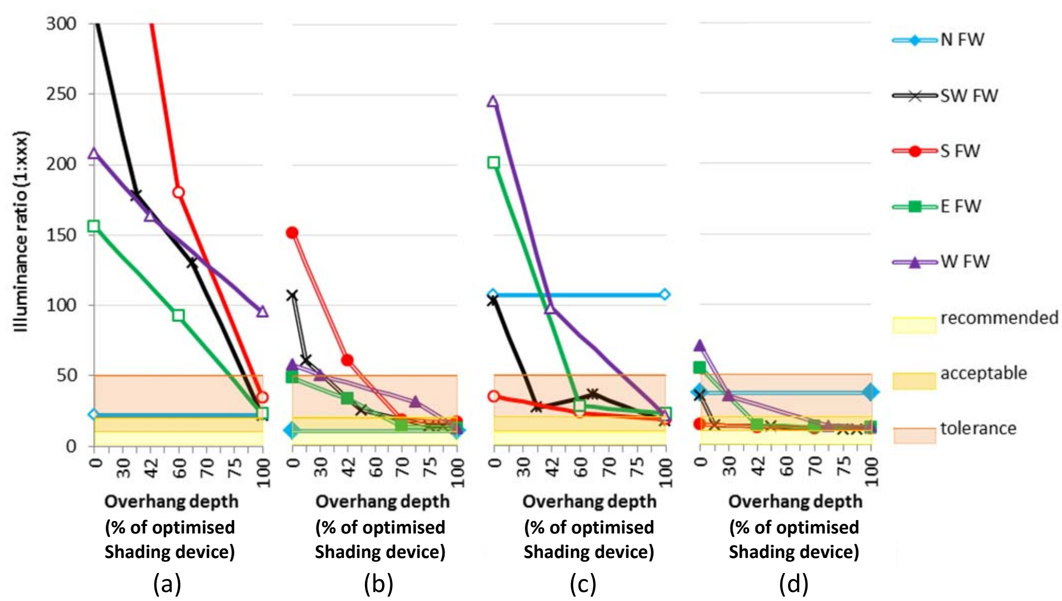


Fig.5. 33 Impact of window orientation and overhang depth on illuminance ratio for (a) base case window in winter solstice, (b) fully glazed wall in winter solstice, (c) base case window in summer solstice, and (d) fully glazed wall in summer solstice

For average illuminance, fanger PMV and cooling load, the graphs are generally in the same pattern (Figure 5.28-5.31). The peaks occur at none shading cases then considerably decrease until about 50% in average of all cases. Over the half of opitmise overhang depth, the reduction rates slightly change to minimum when the window is fully shaded. The values are above thermal comfort scale in every case while they are mostly in the standard range. The limited overhang depth results in excessive high illuminance in some cases particularly in the winter and fully glazed cases. The highest critical orientation is the south which about 40% overhang depth is required to reduce the illuminance down to the upper standards. The great depths of overhang sometimes allow insufficient daylight into the room. The percentage of overhang depth that exceeds 75% generally causes inadequate average illuminance (Figure 5.28 (a) and 5.30(a)). It seems that the depth between 50-75% of optimised overhang should be recommended in general if just the average value of illuminance is considered.

Obviously in Figure 5.32, the greater depths might not significantly improve percentage of the room that illuminances meet the standards when comparing to smaller depth. Moreover, the values are between 40-50% for fully glazed wall cases which is possibly acceptable. In terms of illuminance ratio shown in Figure 5.33, the values are above tolerance rate in general for base case window with less than 75% overhang depth. Differently, they are mostly in at least tolerance area for fully glazed wall cases. Consequently, the 50-75% overhang depth probably can be applied for all orientations with a fully glazed wall.

It can be concluded that influence of window orientation depends on window area and overhang depth. The southwest, south, west and east cases may cause excessive high illuminance and illuminance ratio in a different circumstance, but it provides insignificant results in terms of daylighting sufficiency and thermal comfort. Moreover, the differences of illuminance and cooling load in each orientation can be reduced by increasing overhang depth as well as the difference of illuminance ratio can be dramatically decrease when applying large window area. More than 70% of optimised shading device with fully glazed wall can be recommend to be applied in all orientation with very small different results between orientations. The depth can be reduced to be about 50% if south and east orientations are excluded. The results reveal that penetration of direct sun is acceptable for daylighting. The north is the only orientation that shading device is not requires during working hour. Since, the existing façade provides inadequate daylight level in general, large window area is recommended.

As another solution, adjustable façade may be considered. Window area and orientation may not be able to adjust properly. Therefore, adjustment of shading depth can be the only solution. According to result, depth about 26.25% of optimized device of fully glazed wall is the smallest device for summer solstice. The depth can be applied for shading device in summer solstice and should continually increase until reaching 50% for winter.

5.8 Discussion

There are three key issues that can be discussed for the simulation results. The findings itself presented priority of the focused façade parameters. Compared to previous studies, the solutions can be suggested. Finally, implementation of the solution and its feasibility will be discussed using empirical information from problem monitoring stage

1) Priority of parameters

For this research, three main parameters were investigated using quantitative research method. There are window area, shading device and window orientation. The other parameter which is daylighting control was excluded because the result is more qualitative and appear not be comparative.

According to the results mentioned, window area appears the most significant façade parameter because it can result in sufficient daylight and uniformity but for heat control shading device is always needed. Shading device probably is the second place because all shading depth cases perform unpleasant results with small window area while proper projecting depth was always required for all window area cases and most orientation cases. The orientation appears to have less impact compared to the other parameters because most window area is always required for all orientations and proper overhang depths have to be combined in most cases. Moreover, impact of orientation can be reduced when shading device was integrated. Illuminance is insufficient in general for existing façade especially in summer or in overcast sky condition. It may be improved by adjusting shading device to be less depth in summer because the illuminance in winter is generally useful, but the less window area always provides high illuminance ratio. The two opposite fully glazed walls may not improve much amount of daylight level but it provides the room uniformity better than single fully glazed wall.

In other words, window area is compulsory to be considered in daylighting design while shading depth is an additional parameter that can improve façade more efficient and can reduce impact of direct sun that cause difficulties in daylighting in each window orientation. However, in the case that suggested shading depth does not feasible proper window orientation can lessen the depth of the device. It may be doubtful when suggest considering shading device before window orientation because orientation of the building probably is priority in the early stage of design but the reluctant reaction against this suggestion in the past might be the key barrier resulting in daylighting unsuccessfulness.

2) Façade feature recommendation

While previous research in tropical climates: Maitreya (1979), Chirarattananon et al. (1996), Buriprasert (2000), Chungloo et al. (2001b) and Binarti (2009) suggested window area less than 50% of WWR, the results in this result tend to show that 100% of WWR provides most advantage. Valuing large window area, the results appear similar to some temperate climate findings i.e. Steemers (1994), Inanici and Demirbilek (2000) and Leroux and Gosselin (2012); which thermal comfort strategies are different. Heat protection is less important than tropical climates. Accordingly, Ghisi and Tinker (2005), a tropical climate research, recommended large range of WWR between 20-81% that suitable for narrow room in different contexts. For this research, 100% WWR is recommended to be applied with proper shading projection depth. It implies that large window area will be useful only if the sun radiation is adequately protected. As shading device has been believed to be a key factor of daylight reduction, most previous research in the tropics generally applied only small size of the device. The more depths of shading device are not included in their scope of study. The suggested shading depth of this research is 50% of optimized shading device for fully glazed wall which is four metre depth. This depth of shading can be regarded as a large size of shading that can protect great amount of sun penetration. Since impact of direct sun has been reduced, the result probably closes to suggestion of temperate climate research which the sunlight is normally excluded.

For shading device, previous studies appear to focus on shading types with exact size. Lack of them investigated the proper size. 50% of optimized shading device is suggested in this study. The size stands for the four metre depth for fully glazed wall or shadow vertical angle of 40.5º for southwest orientation. The recommended depth appears to be large shading size whereas existing research findings such as Kim and Kim (2010) suggested very small device at 0.8 metre depth although the research was obtained in upper latitude which not only located in different climate but also generally has lower sun altitude than that in Thailand. A classroom research in Thailand, Saihong and Srisutapan (2007), suggest lower shadow vertical angle at minimally 52º for south orientation which is about 1.6 metre depth for 2.1 metre height window. The suggestion may acceptable in average but when comparing to the recent result the device may not adequate. Suggestions of Saihong and Srisutapan (2007) that intensively investigated effect of combining venetian blind and tilting the device can also imply insufficiency of their suggested device. However, the application of a 4 metre depth shading might be too large for being just shading, but this depth can be either a combination of terrace and overhang when the outdoor space of terrace can advantage use of studios in the upper floor or overhang with dropped edge louvers.

In terms of orientation, many pieces of research recommended to place window in north and south orientation while avoiding west and east. While many recommendations appear to agree to those avoiding directions, the north and south facing was argued by some research. For example, Muhaisen and Dabboor (2015) in the Gaza Strip rated south orientation as the worst condition and Piderit and Bodar (2012)'s finding in Chile implied that north orientation probably provided insufficient daylight in general. In addition, there are some conflict regarding the usefulness of ordinal direction what still question. One research in Brazil (Zannin et al., 2008) confirmed that the low angle sun of ordinal orientation can benefit daylighting while another in Thailand (Saihong and Srisutapan, 2007) stated that it is difficult to control. According to some recent findings, the result partly agrees with the majority of previous researches for the benefit of north orientation and difficulty to control excessive high daylight level from south, southwest, west and east orientations. According to Ghisi and Tinker (2005) in Brazil and Le Hong and Rodriques (2013) in UK, more window area was recommended for south orientation while less area was suggested for the north. The suggestions appear opposite to the finding of this study particularly for north orientation that daylight level is generally insufficient. Despite the fact that north orientation general provides inadequate daylight, it can be useful if large window area was applied. It is because the façade in this facing required very less projecting depth: no shading during working hour for this study. For the other orientations, the recent results show that they provided worst daylighting environment in different context with existing window and less than 50% of shading depth. This research found the disparate result regarding difference of orientation. It is reported that with 50% of shading depth or over the results of each orientation are not much different. However, it might be impractical to use up to four metre depth shading devices in buildings because they can affect appearance, cost and maintenance of the building but typical feature of general classroom that connected to corridor in the opposite side of the window can make the suggested shading depth become feasible. With at least 2.5 metre width of public building corridor forced by Thailand Building Control Act B.E.2522 (1979), the additional depth required is only 1.5 metres. Moreover, in some cases of design such as in the case study building, the wide corridor was assigned to be not only walk way but also recreation terrace. Therefore, the less depth solution supposed to be integration of north window orientation which required no shading and south facing corridor which total shading depth at least four metres. The suggestion obviously supports the need of two opposite side window.

There are some previous studies (e.g. Tanner, 2000 and Heschong et al., 2002) affirmed that to add one or more windows in other walls of the room can benefit daylighting in general but none of them provided details about orientation and size of the window including its shading. The recent findings tend to confirm those suggestions with recommended of two opposite fully glazed wall with shading depth at least 50% of optimized device in each orientation.

Consequently, window area is recommended to be fully glazed wall for both sides of classroom façade with 50% shading depth of optimized shading for all orientations. While more feasible shading design could be two opposite fully glazed walls applying north window orientation without shading and 50% shading depth of south facing corridor.

3) Implementation

The simulation results report that the suggested solution is practical for general learning activities. The solution can solve insufficient and variation problems of existing classrooms in general. Artificial light integration may be required in some case such as overcast sky that can be occurred in some days in rainy season. With suggested shading device, the results reveal that façade operation is probably not needed except when using projector. However, the quantitative result may not be able to confirm real visual comfort for lighting environment. The solution allows penetration of direction especially during late afternoon in winter. It is doubted that may cause visual discomfort. Although there are evidences: Boubekri and Boyer (1992) and Denan (2004); that occurrences of glare can be occurred only if occupants sit facing to light sources, negative effect of direct sun was mentioned by the survey participants. Despite the fact that majority of building users preferred bright environment and informed that glare was not generally occurred, effect of direct sun especially during winter should be empirical proved that does not cause visual discomfort. Apart from lighting environment issues, the large window may affect occupants in their learning attention and privacy. Although previous research: Tennessen and Cimprich (1995) and Fisher et al. (2014); affirmed that good view can benefit adult students' learning attention, their satisfaction in terms of attention and privacy is still a question. It is because the additional window connected to corridor. With this window, not only people outside can distract the students, but the occupants may also feel not private. Occupant satisfaction in terms of visual comfort, learning attention and privacy are required to be confirmed.

The solution appears difficult to implement especially for window orientation. In actual situation, orientation cannot be changed, therefore, the 50% of overhang depth should be applied for either fixed or adjustable device. Fortunately, existing shading depth of the corridor is sufficient. In addition, two walls of the room should be changed to be glazing area. The building structure is reinforced concrete slab on beam. The building envelope mainly is brick work. Therefore, it is feasible to be changed but costly and not easy.

Daylighting control system consisted of artificial light and shading device operation systems is the other importance parameter that influences efficiency of façade feature. In order to achieve good daylighting, apart from façade appearance, operation systems should be practical. For external shading device, if the device is fixed, the operation will not be required. The device needs to be operated when adjustable solution is selected. According to survey, the users themselves rarely operated the curtain. The reasons could be the existing façade cannot provide proper daylighting environment but one of the main reasons is it must put an effort to operate the existing blind. It is obvious that the occupant always closed the blind for using projector and switched on the light after finishing projector use. Artificial light provided not only brighter environment but also easier to operate. This information may reveal less feasibility of adjusting external shading devices, but the survey inform that administration staffs are also responsible for room operation. Therefore, as very few times of the year that the device is required to be adjusted, the operation of adjustable devices can be more effective if it is included in the staffs' job description. Internal shading device has mainly used for controlling. For existing window, the blind occlusion was generally occurred then using projector. For the suggested façade feature, except for using a projector, the need for blind occlusion tends to be rare. However, the effect of sun penetration, which has been assumed in this study that will not cause visual discomfort, can result in glare or discomfort. In that case, adjustable venetian blinds were suggested in many pieces of research (e.g. Dubois (2003) and Kim and Kim (2010) that can solve the problem. With the devices, the predictions which were supposed to be different were exactly the same as the base case, which is a weakness of DesignBuilder. The need for the device is still a question. The issue probably results in different design consideration. If glare control is needs reflective or diffused device is required whereas if it is not, only opaque device is needed. Their cost and operation method are also distinct. However, internal shading and artificial light are necessary in case of projector use and when it is low illuminance from the sky. Simple controller at teaching area is required for these issues. Additionally, noticeable sign for insufficient lighting environment should be integrated.

In this chapter, the availability of daylighting in existing classrooms was approved with suggested façade solutions. The results appear to be sensible, but proof of practicality may be needed. The effect of direct sun and occupants' sensation for suggested façades in terms of learning attention and privacy is required to be studied.

Chapter 6

Application

In order to suggest classroom façade design solution, confirmation is required for the simulation stage. This is because simulation programs cannot assess visual comfort sensation. Only one case study cannot validate a generalisation of a climate zone. In this chapter the application of façade design solutions will be reported for not only investigating users' satisfaction but also generalising the solutions to other case studies in the areas. In order to consider other relevant façade parameters, additions of reflecting strategy and effect of façade feature on natural ventilation are included at the end of this chapter.

6.1 Application of the suggested solutions

According to the simulation results, the most proper solution tended to be two opposite fully glazed walls with a four metre depth overhang. This size of shading device allowed direct sun to penetrate the room, especially on winter afternoons. Since discomfort of lighting environment can occur in this condition, occupants' satisfaction survey and physical measurement were obtained during December 2014 to January 2015 in the modified classroom in order to study actual effect of the suggested façade comparing to the existing classrooms.

1) Modified classroom

The modified classroom was set in an exhibition area on the ground floor under the base case classroom: AR206. When first built the area used to be a large unenclosed area adjacent to opaque walls of a storage room and a stair case. It was refurbished to be an exhibition area later by enclosing the space with fully glazed walls - clear glass with an aluminium frame. With two opposite fully glazed walls, the room has the same width as the existing classroom which is 10.4 metre, about a third times its length and 3.8 metre high. The window was shaded by trees and an overhang of the upper floor. The opposite wall connects to a corridor facing to the central court. The corridor may not be the same width as the base case, but the shading depth is the same as the device is the floor of base case corridor. Room colour is normally white except the ceiling, which was painted grey. The room was walled to be the same length of the existing classroom, which is 10.4 metre, using white exhibition panels and filled with similar furniture to general classrooms of the building. The differences of the setting room from the existing classroom consisted of the facades, ceiling colour and height which is 0.4 metre higher. The room appearance is illustrated in Figure 6.1.

Fig.6. 1 Modified classrooms of two opposite fully glazed walls

Fig.6. 2 Daylighting condition of the modified classroom during January 2015 in different times: (a) at 10AM, (b) at 2PM and (c) at 4PM

During January 2015, the sun penetrated onto the room significantly in the afternoon. As can be seen in Figure 6.2, the room is bright without sun penetration in the morning (Figure 6.2(a)) while it was affected by direct sun in the afternoon. The sun path changed in different times. For example, sun penetrated at the first four seats from the window during 2PM (see Figure 6.2(b)) while it was in almost all areas of the room at 4PM (shown in Figure 6.2(c)). According to the observation, the daylighting environment is supposed to be bright in general with a high potential of glare occurrence. The empirical study should be investigated to confirm whether the worst case of modified room will cause visual discomfort or not.

2) Daylighting environment

The measurements were obtained during January 2015 in the modified classroom and the base case: AR206 using a Hagner lux meter for 30 measured positions with four HOBO loggers for calibrating daylight fluctuations. In this case, daylighting conditions at various times were studied. The comparison of the modified case to the base case is illustrated in Figure 6.3 and 6.4. In the morning when there is no influence of direct sun, the illuminance of the two fully glazed walls case is 200-300 lux higher than the base case in average without artificial light (see Figure 6.3). Although illuminance is higher, further than half the distance from the window it is lower than standards. However, when comparing to the sensation vote, the level is in *slightly bright* level which may not be occupant' preference but appears to be acceptable. When there was sun penetration in the afternoon (see Figure 6.4), daylighting level of the fully glazed walls case met standards in general. It was only the area closed to the window that illuminance was higher than 2,000 lux.

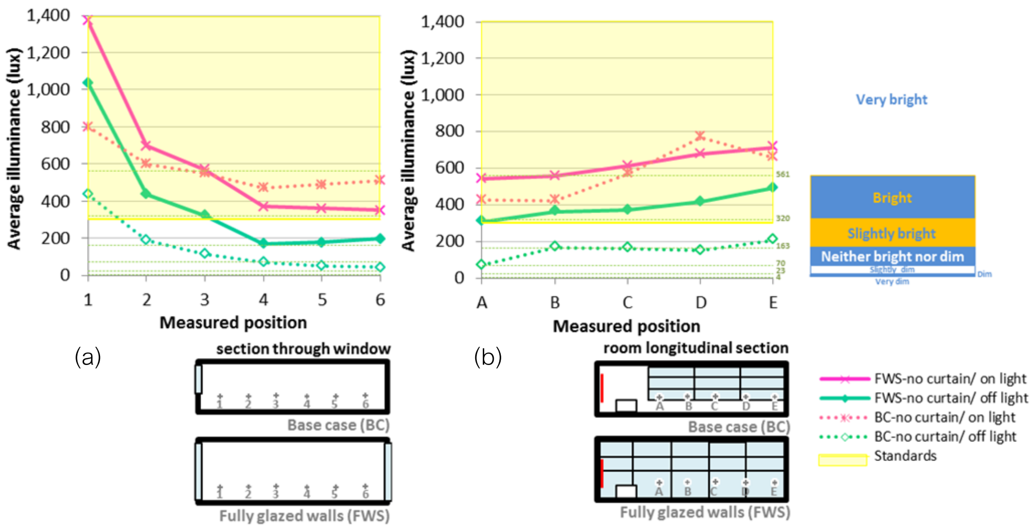


Fig.6. 3 Average illuminance of daylighting and artificial light integration environments in the morning: (a) through window and (b) longitudinal section of the room.

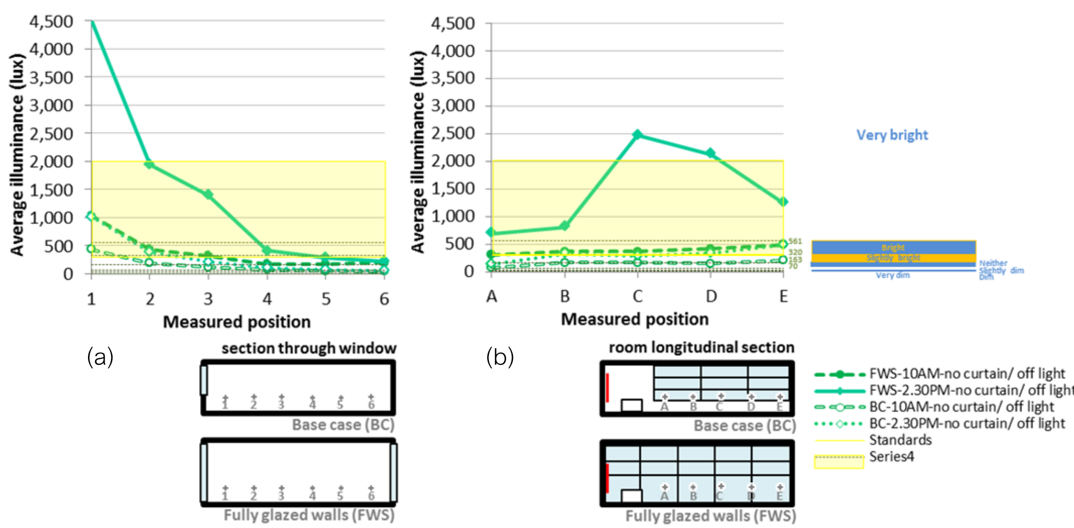


Fig.6. 4 Average illuminance of daylighting environments in the afternoon: (a) through window and (b) longitudinal section of the room.

For the lighting integration case shown in Figure 6.3, it was about 200-300 lux higher than the daylighting case. Unexpectedly, the lighting case of the fully glazed walls case is about 100 lux lower than that of the base case at the furthest area from the window. This might be because of the darker colour can the higher height of the ceiling that absorbed artificial light more.

The amount of daylight for the modified case appears to be sufficient but with more variation. The daylight distribution is presented in Figure 6.5. The measurement of the lighting case (Figure 6.5(a)) is the only case that the lighting uniformity closed to recommendation. Daylighting cases (Figure 6.5(b)-(c)) result in excessive high variation especially when sun penetrated the room in the afternoon. Interestingly, the illuminance ratio at 1.30PM which contained a smaller penetration area, is significantly higher than that at 2.30PM. It may be because the intensity of the sunlight from the vertical overhead sun is higher than that from lower sun altitude. It reveals that shading device is required mostly for the higher sun altitude and the need increases when the sun move to lower position. It agrees with the simulation result that the overhang is definitely requires but optimized shading is not necessary. Penetration of the sun can benefit daylighting in late afternoon.

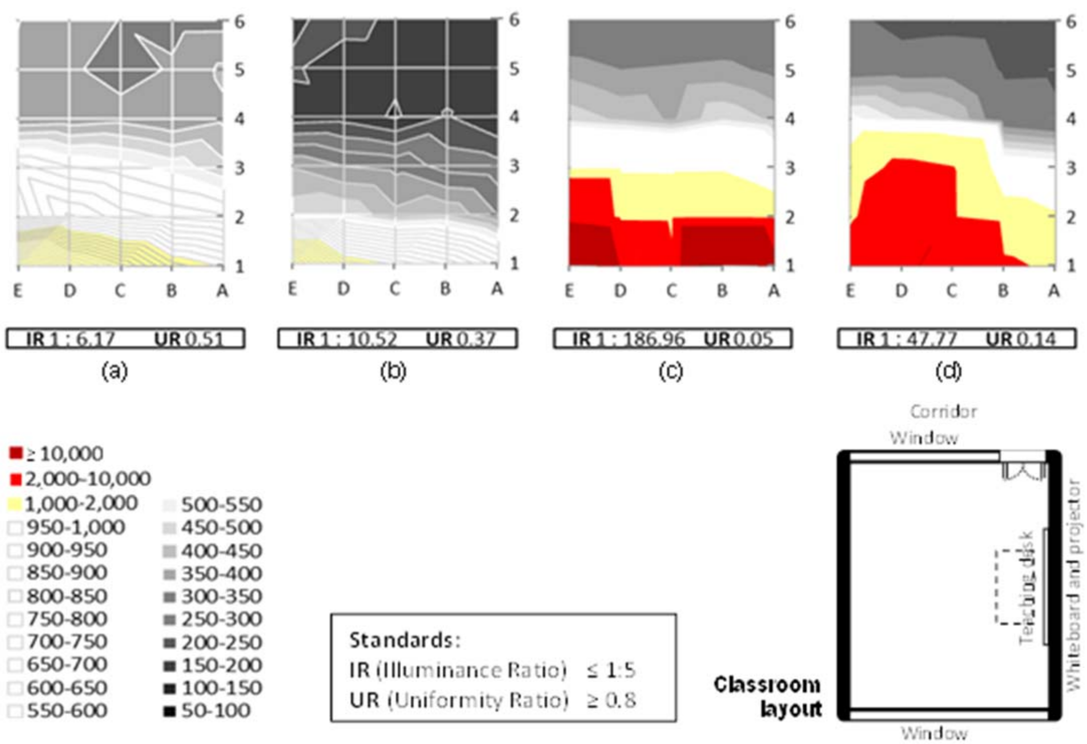


Fig.6. 5 Conditions of illuminance distribution during 12nd-13rd January 2015: (a) switched on light at 10AM, (b) switched off light at 10.30AM, (c) switched off light 1.30PM and (d) switched off light 2.30PM

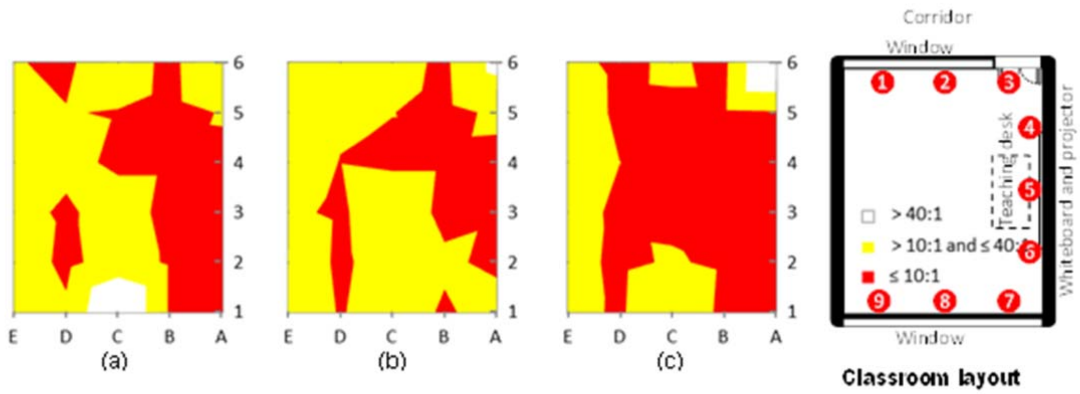


Fig.6. 6 Maximum and minimum luminance ratio of 30 measured points during 12nd-13rd January 2015: (a) switched on light in the morning, (b) switched off light in the morning and (c) switched off light in the afternoon

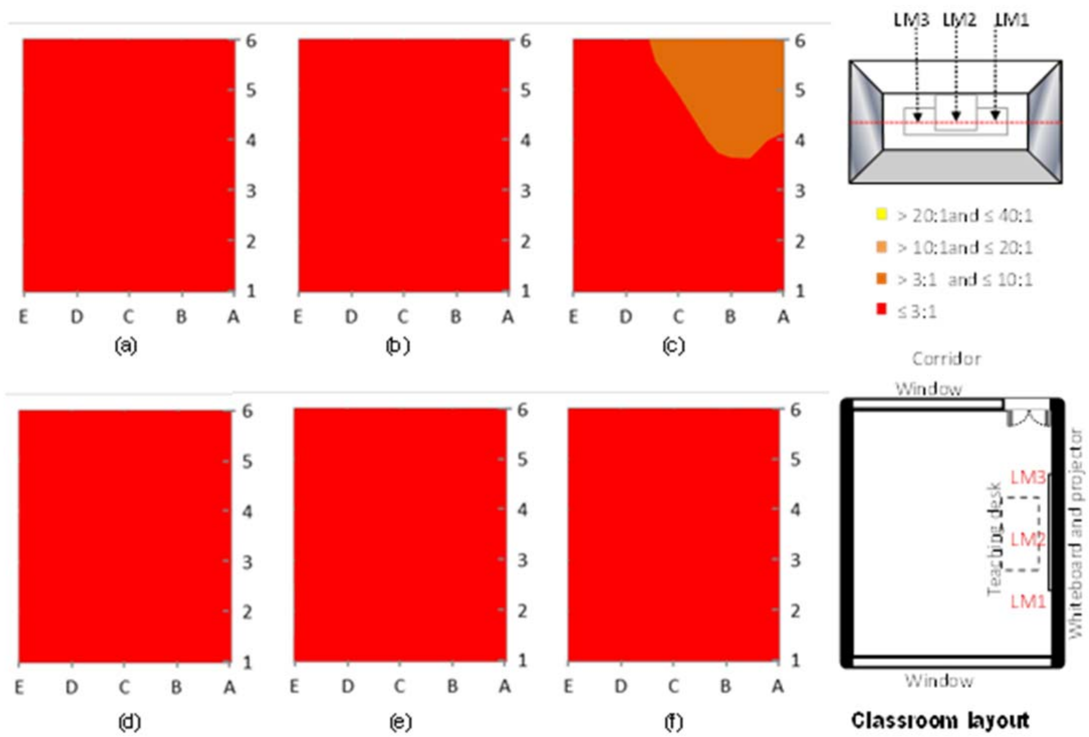


Fig.6. 7 Luminance ratio of projector screen (LM2) and its background (LM3 or LM1) of 30 measured points during 12nd-13rd January 2015: (a) LM2/LM3 switched on light in the morning, (b) LM2/LM3 switched off light in the morning, (c) LM2/LM3 switched off light in the afternoon, (d) LM2/LM1 switched on light in the morning, (e) LM2/LM1 switched off light in the morning and (f) LM2/LM1 switched off light in the afternoon

Differently, for vertical luminance, the daylighting conditions (Figure 6.6(b) and (c)) performed better luminance ratio than the lighting integration case (Figure 6.6(a)). The case in the afternoon generally has fewer ratios than the other cases. For luminance ratio of the projector and adjacent surroundings (see Figure 6.7), it met standard in all case. However, the ratio is little higher at the further area of the window in front of the room for the ratio of projector screen luminance (LM2) to further adjacent surface from the window (LM3) in the daylighting condition in the afternoon (shown in Figure 6.7(c)).

Consequently, the modified classroom resulting in adequate daylight level in general but the excessive high variation of it can be questioned. While excessive high illuminance ratio tends to represent visual discomfort, the results of vertical luminance rather reported differently. This conflict was solved by asking the room occupants for their lighting satisfaction.

3) Occupant satisfaction

Occupants of the existing classroom were asked to fill the questionnaire (details shown in Appendix A) about their sensation of the lighting environment of the two opposite fully glazed walls classroom. When the occupants were asked to compare the new room to their common classrooms, teachers and students voted differently (details shown in Figure 6.8). The majority of teacher voted that the modified classroom had better lighting environment while student vote worse the most. Although the vote for worse is majority, the sum of better and same is little higher. It reveals that only minority of the occupants thought the fully glazed case has worse lighting condition than their existing classrooms.

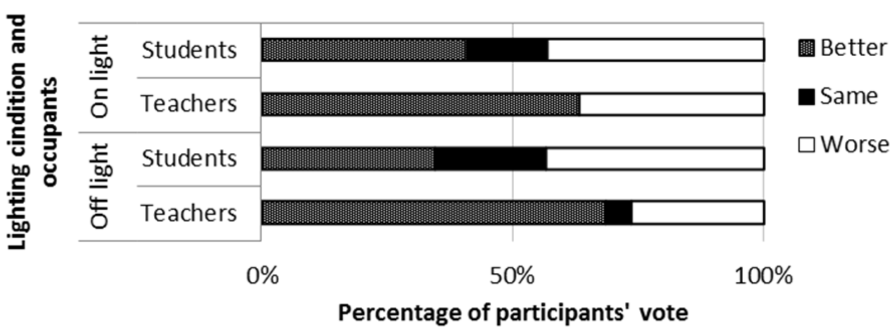


Fig.6. 8 Participants' vote on their lighting satisfaction of the modified classroom comparing to their common classrooms.

Most of the participants voted their lighting sensation of the modified classroom as it being a bright environment (see Figure 6.9) and they preferred no change for the provided conditions (Figure 6.10). Although the occupants thought it a bright environment, they preferred brighter than dimmer conditions. The results appear to agree with the former survey that the bright environment is always the occupants' preference. When considering the vote from the former survey in Fig.4.36, the sensation vote for off light condition in the modified room tends to be brighter rate. Most participants in the existing classroom required brighter conditions while no change was mainly voted for the modified classroom.

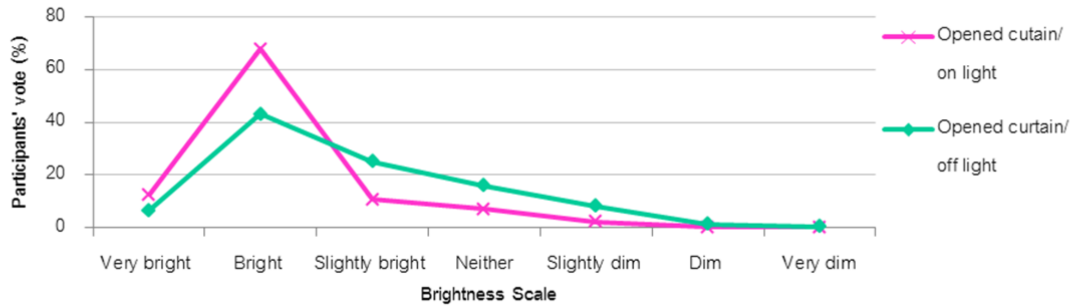


Fig.6. 9 Participants' vote on the room brightness for daylighting and artificial light integration environments.

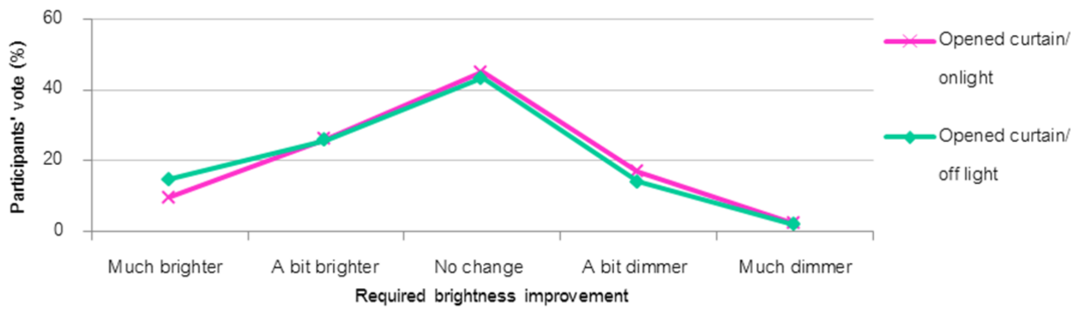


Fig.6. 10 Participants' requirement for brightness improvement for daylighting and artificial light integration environments.

For the three visual tasks, votes of visual comfort are shown in Figure 6.11. As expected, the occupants voted comfort mostly for the lecture desk while most of them thought it was discomfort for seeing whiteboard and projector screen. Although exhibition panels were used instead of the whiteboard containing a semi-glossy surface, the participants still ranked discomfort a little more than comfort. It reveals that not only the direct reflection from glossy surfaces but also the diffusing light from the white surface can cause visual discomfort. The brightness appears too much to see task on projector screen properly that the contrast of the image and quality of the device can be a major part of this issue.

When comparing to the previous survey in Figure 4.40, the participants appeared to the prefer lighting environment of the existing classrooms more than the modified classroom when artificial light was combined for seeing tasks on lecture desks and whiteboards. On the other hand, they prefer the modified classroom more without lighting. For using the projector, the existing classroom tends to be better as it is dimmer.

According to result in Figure 6.12, about 30% of participant thought that there is glare in the modified classroom. The lighting condition is 20% lower than existing classrooms whereas the daylighting condition is

20% higher (see Figure 4.41). This means that although the fully glazed walls case always brought about a higher illuminance, the lighting condition of the existing classroom probably cause much votes of glare. It implies that more illuminance is not always more glare.

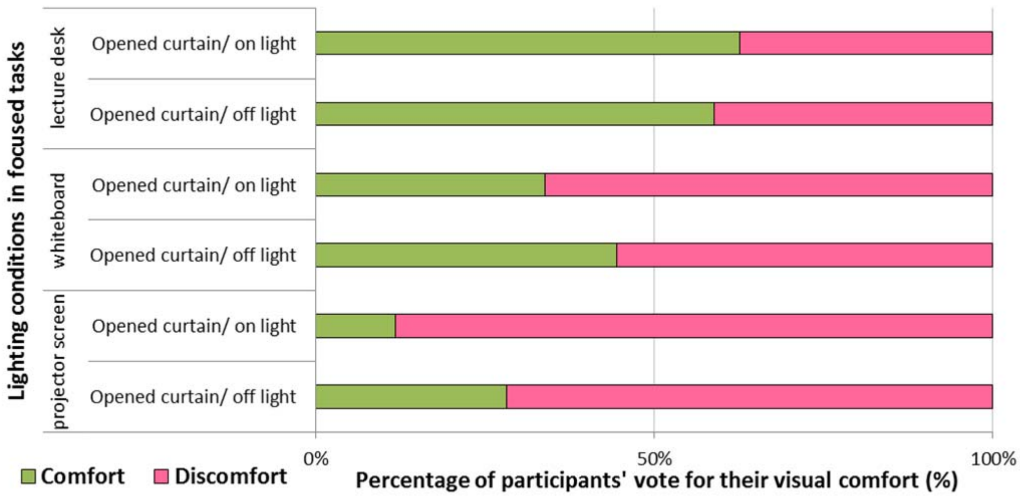


Fig.6. 11 Votes of visual comfort on three focused tasks in daylighting and artificial light integration environments.

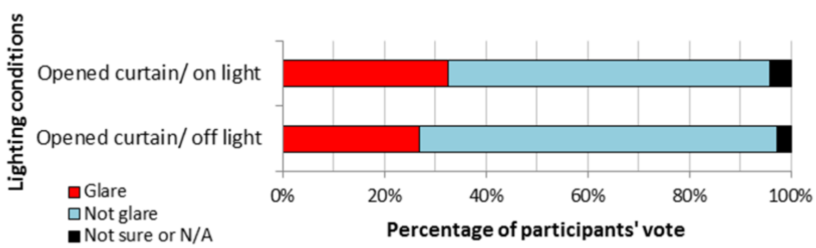


Fig.6. 12 Participants' vote about glare for daylighting and artificial light integration environments.

As can be seen in Figure 6.8-6.11, there might be differences between daylighting conditions and artificial light combination conditions. Although the lighting condition provided more illuminance, it appears to cause more visual discomfort. However, apart from no significant difference shown in the result especially in Figure 6.10, the required brightness improvement is almost the same as the daylighting condition; there were a lot of additional comments indicating that the participants thought there was no difference between the two conditions.

4) Privacy and Distraction

In order to avoid influencing occupants, the questionnaire intentionally did not specify about privacy and distraction problems which can occur in such a transparent space like a fully glazed room but comments about these issues were expected in some open-ended questions provided. The answers mostly mentioned that the room was open and too bright. None of comments specified dissatisfaction in feeling not privacy or being distracted. As observation, there also was no sign indicating that the participants were disturbed from outside when they sat and filled questionnaire. However, it is noted that doing questionnaire might be different from the real class.

6.2 Generalisation

The suggested solutions which were discussed are also applied to three additional case studies which are representatives of other regions in order to examine successfulness of the solutions in general. The applications focus on effect of the suggested façade feature on daylighting.

1) Results of daylighting analysis

Daylighting in five case studies were investigated using daylighting analysis program DIALux. Suggestions of classroom façade for daylighting were modelled and simulated. In this part, significant results of each classroom will be reported.

a. Room AR207 of Arch MSU

As the main case study, room AR207 was simulated in order to use as the base case for referring to the results in chapter 5 which were studied in different time using another device and for validating differences of weather data in the four cases that cannot be obtained at the same time.

The daylighting analysis in different times and sky conditions can be seen in Figure 6.13 – 6.17. The graphs show effectiveness of the solution of four metre-depth overhang and two opposite fully glazed walls for overcast sky condition and sunny clear sky condition from 22nd of June to 22nd of December. Despite some different patterns in summer and winter due to window orientations, the solution provides most illumination level and uniformity in general. Furthermore, the suggestion also can better shade the low angle sun which cause excessive high illuminance than the base case.

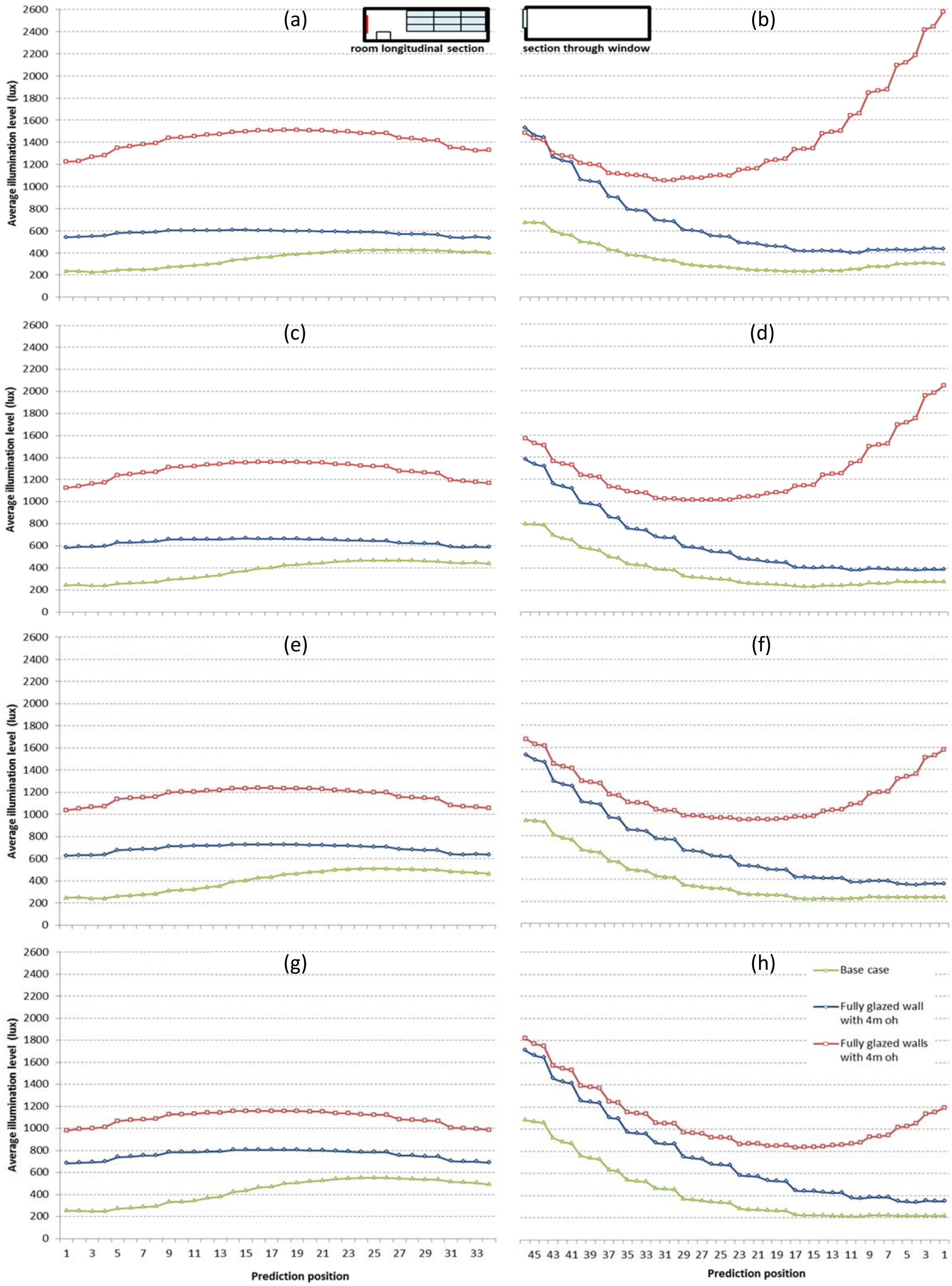


Fig.6. 13 Prediction of average illumination level under sunny clear sky in AR207 of Arch MSU on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

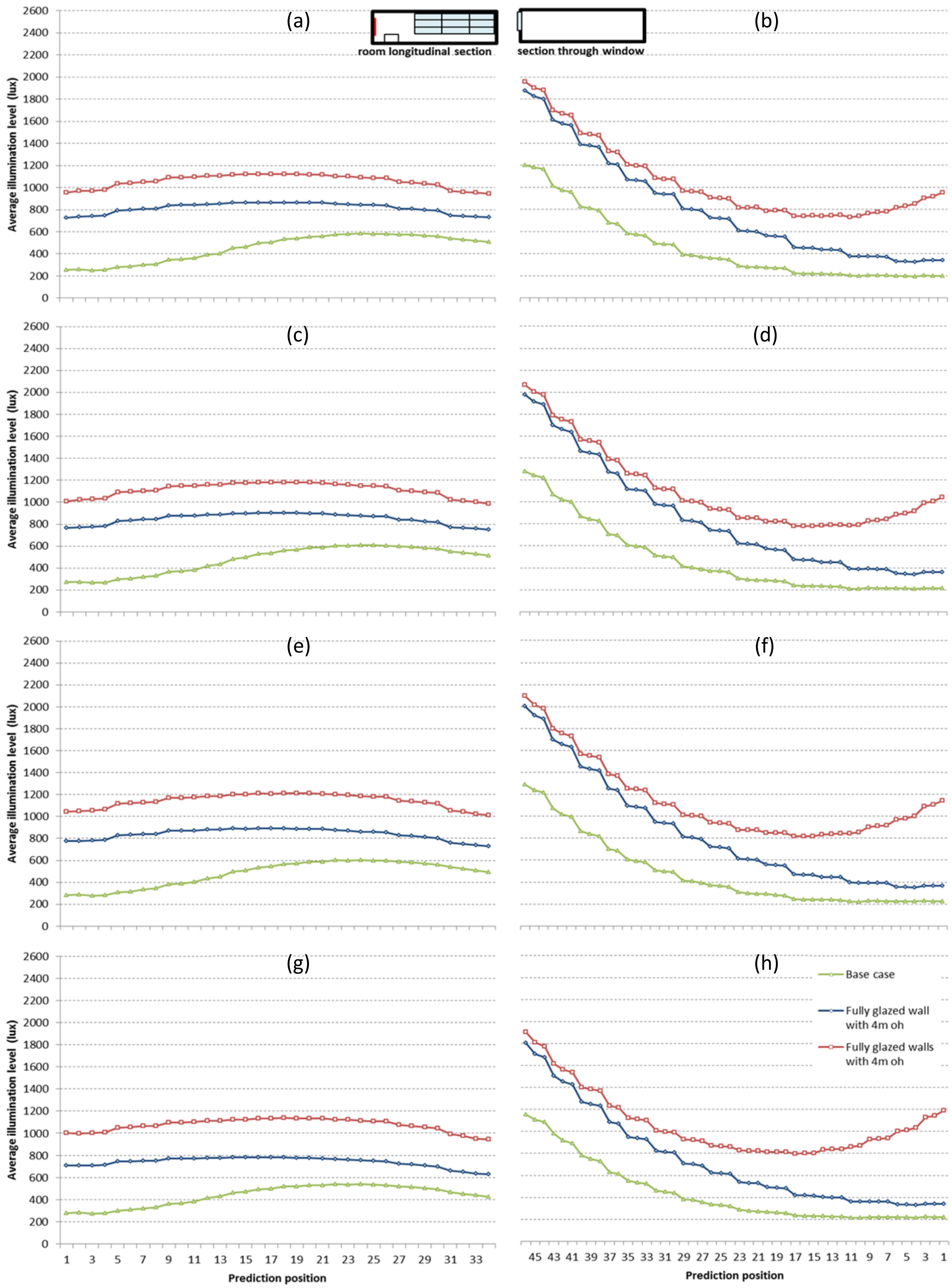


Fig.6. 14 Prediction of average illumination level under sunny clear sky in AR207 of Arch MSU on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

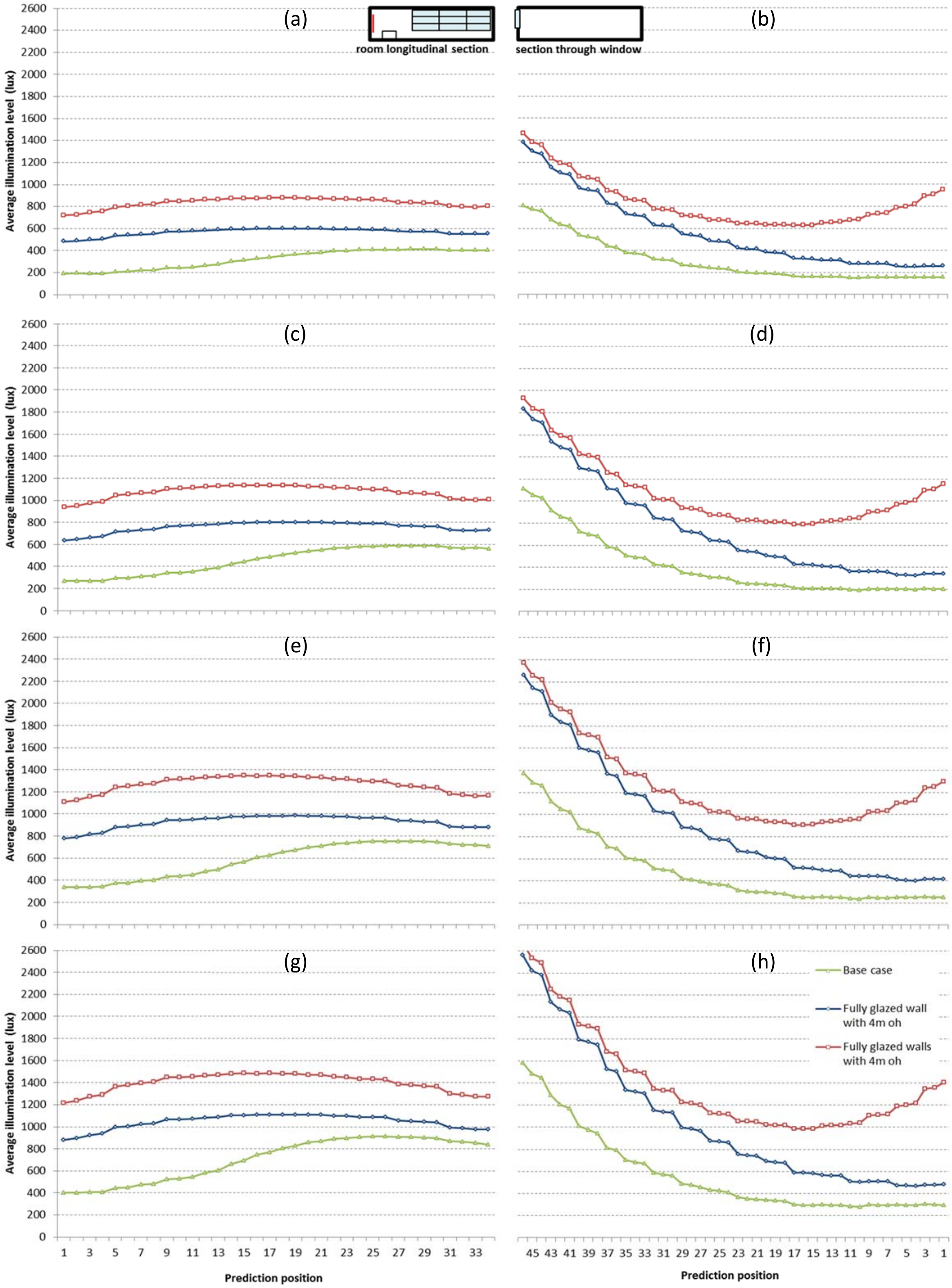


Fig.6. 15 Prediction of average illumination level under sunny clear sky in AR207 of Arch MSU on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

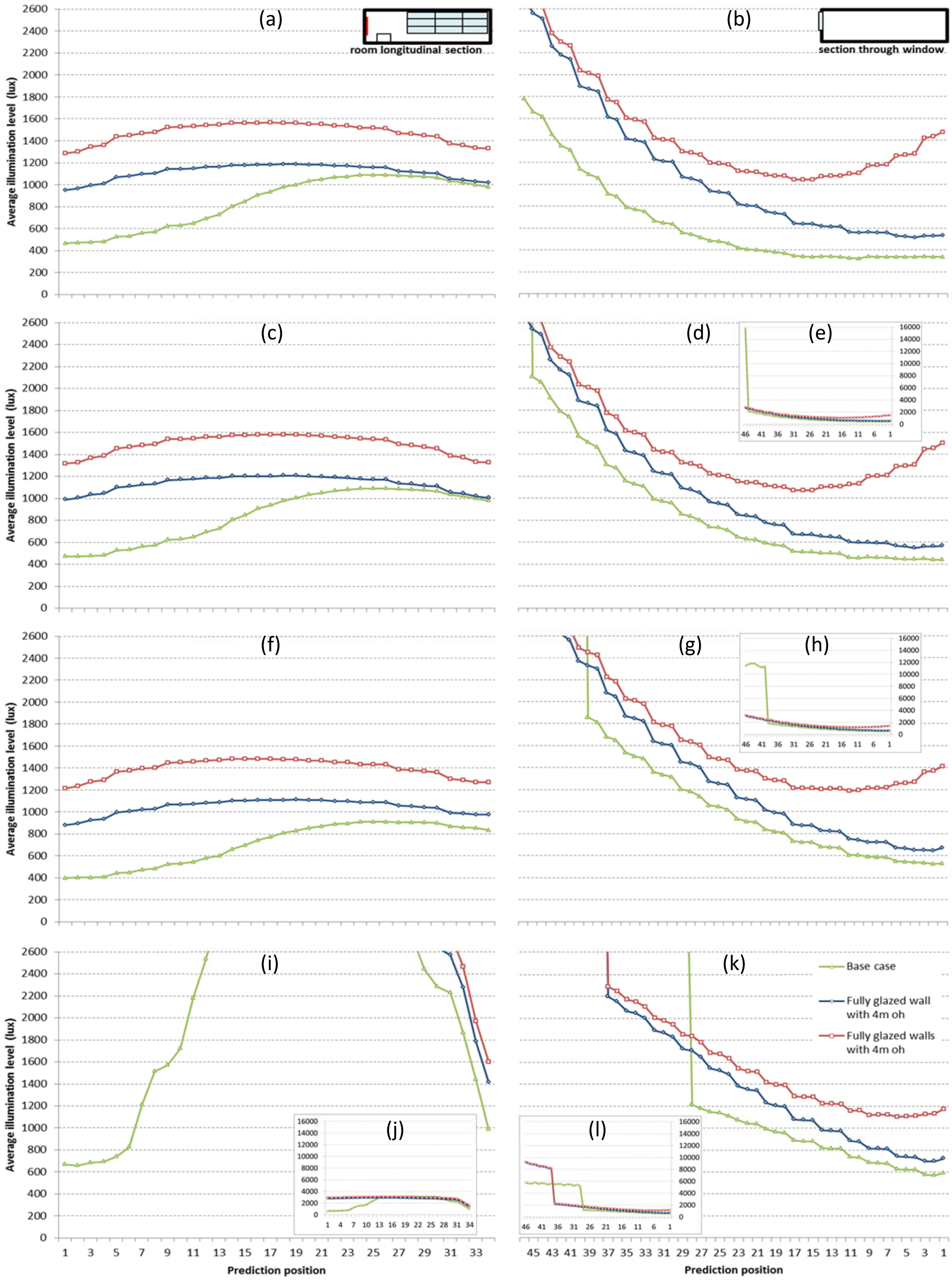


Fig.6. 16 Prediction of average illumination level under sunny clear sky in AR207 of Arch MSU on 22nd Dec. (a)-(b) 13:00, (c)-(e) 14:00, (f)-(h) 15:00 and (i)-(l) 16:00

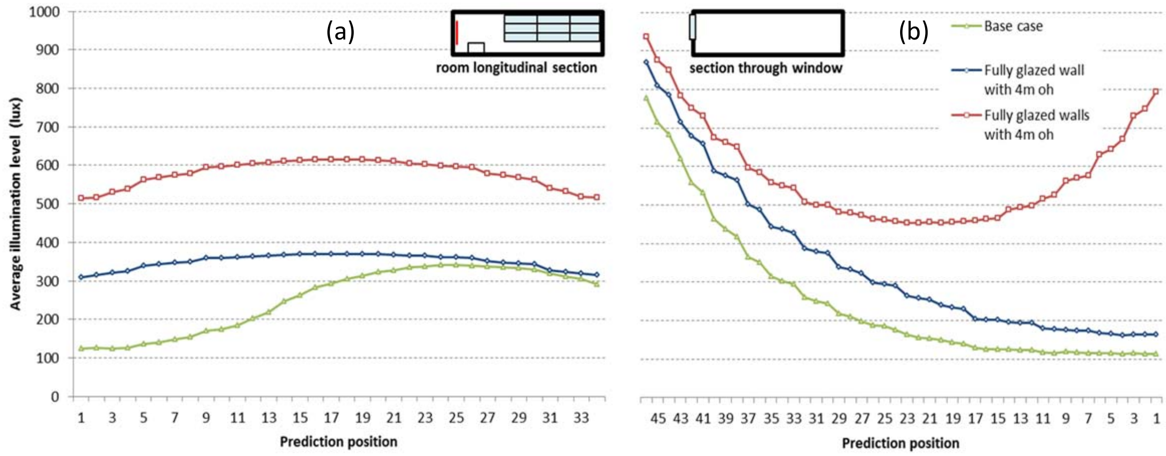


Fig.6. 17 Prediction of average illumination level under overcast sky in AR207 of Arch MSU. (a) by room longitudinal section and (b) room cross section

As shown in Figures 6.13 –.6.17, daylighting problems in AR207 Arch MSU, which is a single sidelit room, were very general - excessive high illuminance in front of window but insufficient lighting in the furthest area. The contrast between the lowest and highest illuminance also cause visual discomfort for the room occupants. The main suggested solution in this study which can optimise quantity of daylighting and provide daylight distribution most uniform. According to the previous chapter, the two opposite fully glazed walls with four metre depth overhang was found as the proper solution in most of working hour in terms of thermal and daylighting for both quantity and quality. The daylit opening at the corridor side can not only increase illumination level in the mid and back of the room but also result in lighting uniformity of the room in general. Although the room width is more than daylighting recommendation (six metres by Steemer (1994) and seven metres by Tangpoonsupsiri (2001)), the daylight illuminance meets the standard of 300 lux in most of the time. However, the fact that classroom feature of Arch MSU can differ to other classrooms in the same size can cause the suggested solution to be doubtful. The three following cases were also studied. Their specific features that result in different results were discussed.

b. Room 1712 of Sc SWU

For room 1712 of Sc SWU, the fact that the main windows face to the east causes different illumination pattern. The daylight affects the room the most in the morning. However, the reduction of illuminance through the window is in the same direction. The suggested solutions which are the fully glazed wall cases with overhang were analysed. For this specific orientation, the 50% of optimum overhang is 2.5 metre depth.

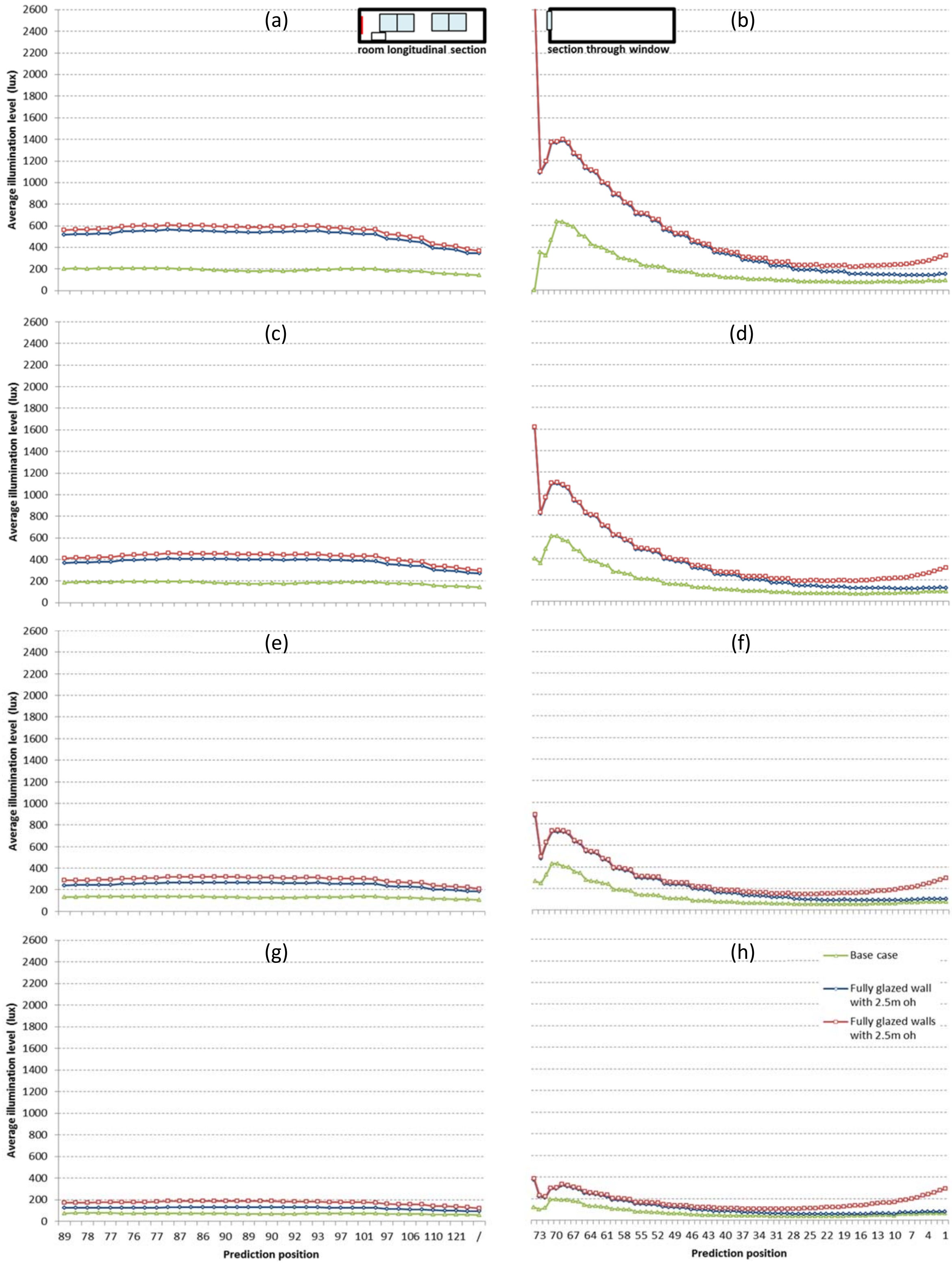


Fig.6. 18 Prediction of average illumination level under sunny clear sky in room 1712 of Sc SWU on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

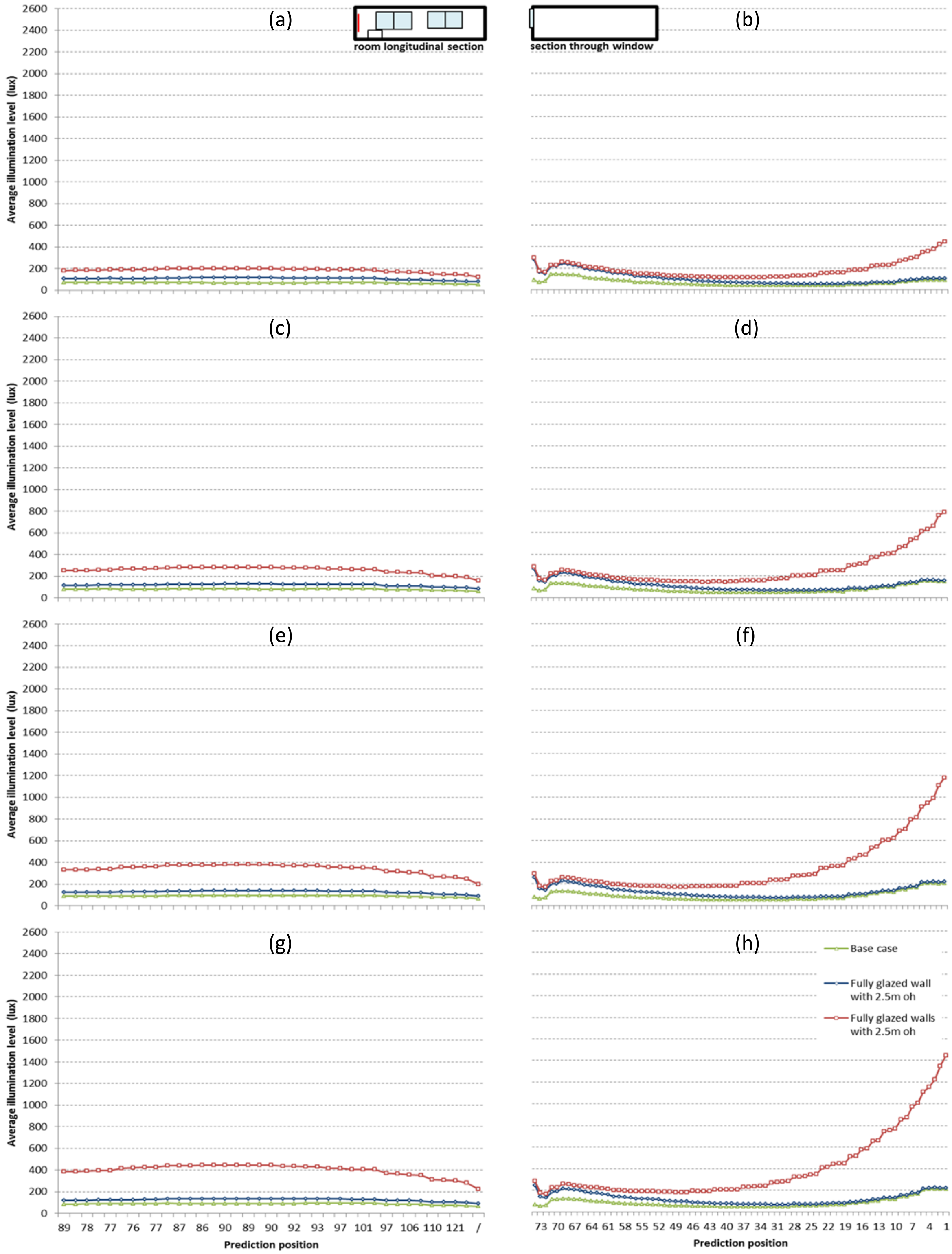


Fig.6. 19 Prediction of average illumination level under sunny clear sky in room 1712 of Sc SWU on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

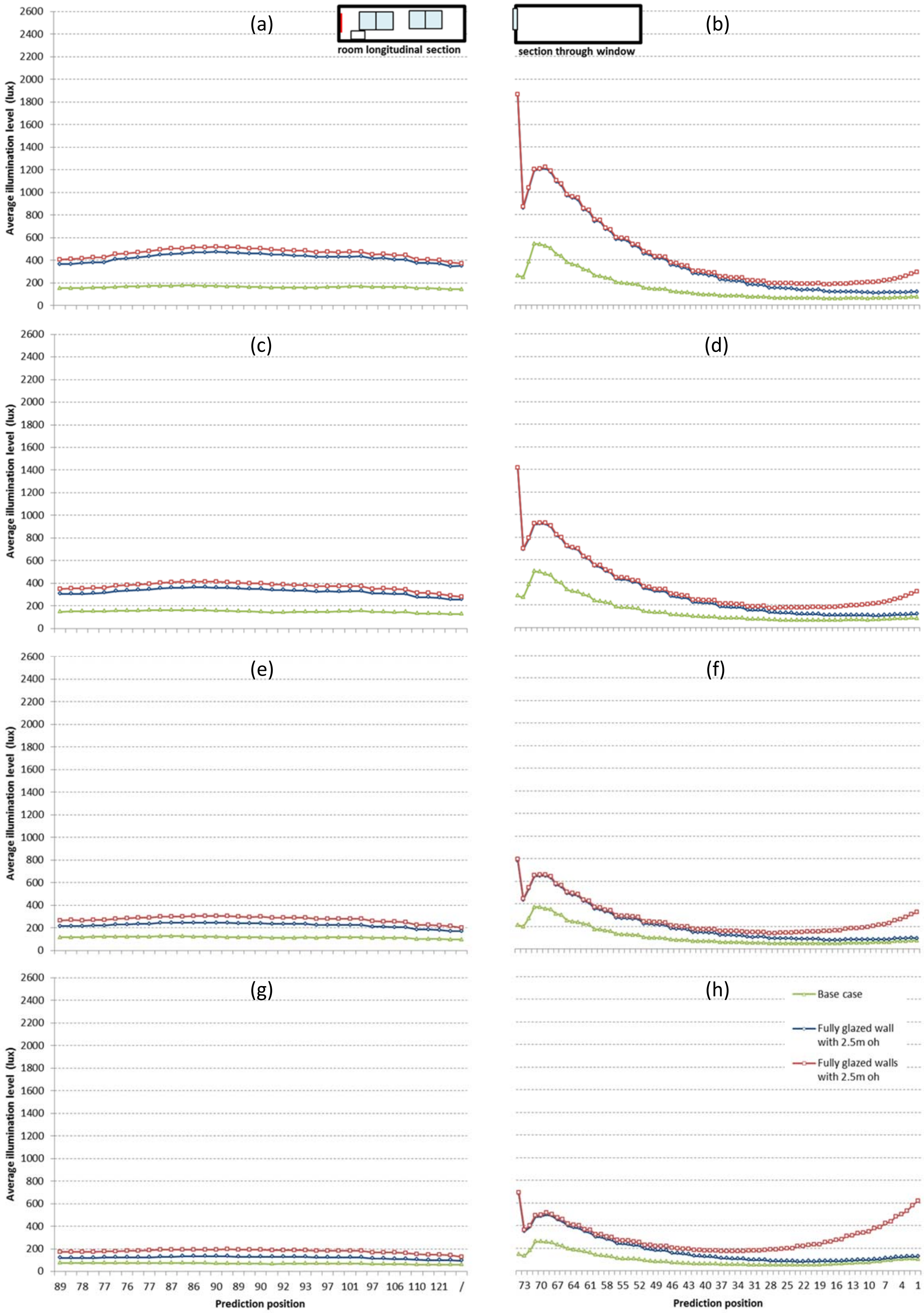


Fig.6. 20 Prediction of average illumination level under sunny clear sky in room 1712 of Sc SWU on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

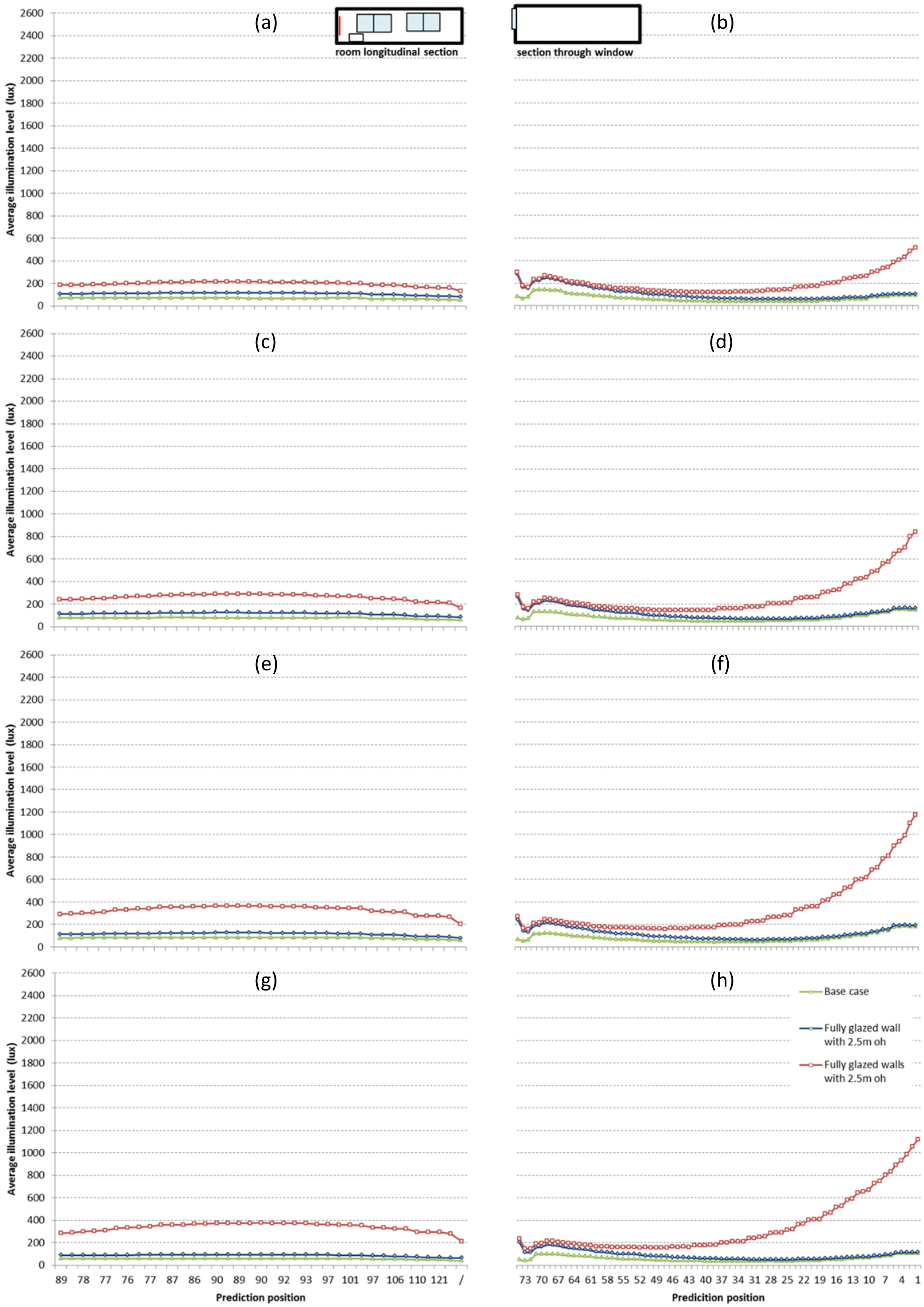


Fig.6. 21 Prediction of average illumination level under sunny clear sky in room 1712 of Sc SWU on 22nd Dec. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

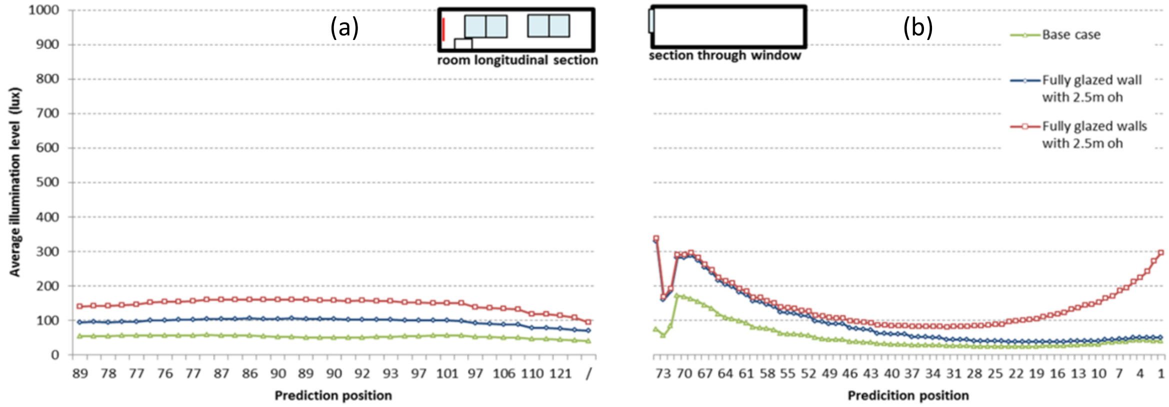


Fig.6. 22 Prediction of average illumination level under overcast sky in room 1712 of Sc SWU By (a) room longitudinal section and (b) room cross section

The excessive width of the room 1712 causes daylight illumination levels in the room to be considerably lower than that in the main case study, especially in the middle of the room, which is the area of lecture desks. With that width, the majority of room illuminance no longer meets the standard. Actually, the 16 metre width of the room appears too large for the existing area of lecture desk which is approximately 7.5 metre in width. It reveals possibility of daylighting sufficiency if the room is functioned to be lecture room since its first design and the 7.5 metre room width is applied. However, the fact that the purposed two opposite side windows face to the east and the west can be difficulties. East and west orientations are greatly influenced by the sun in very limit hours for the classroom operation time, early morning and late afternoon. Amounts of daylighting input for these orientations therefore are also less than the main case study which is influenced by the direct sun in most times of the day and the year.

c. Room 5111 of Sc CRRU

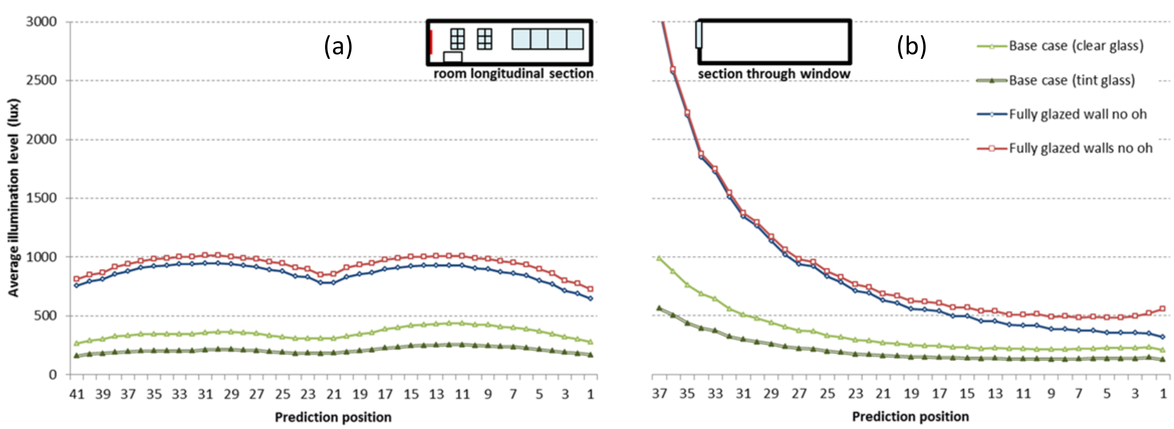


Fig.6. 23 Prediction of average illumination level under overcast sky in room 5111 of Sc CRRU. (a) by room longitudinal section and (b) room cross section

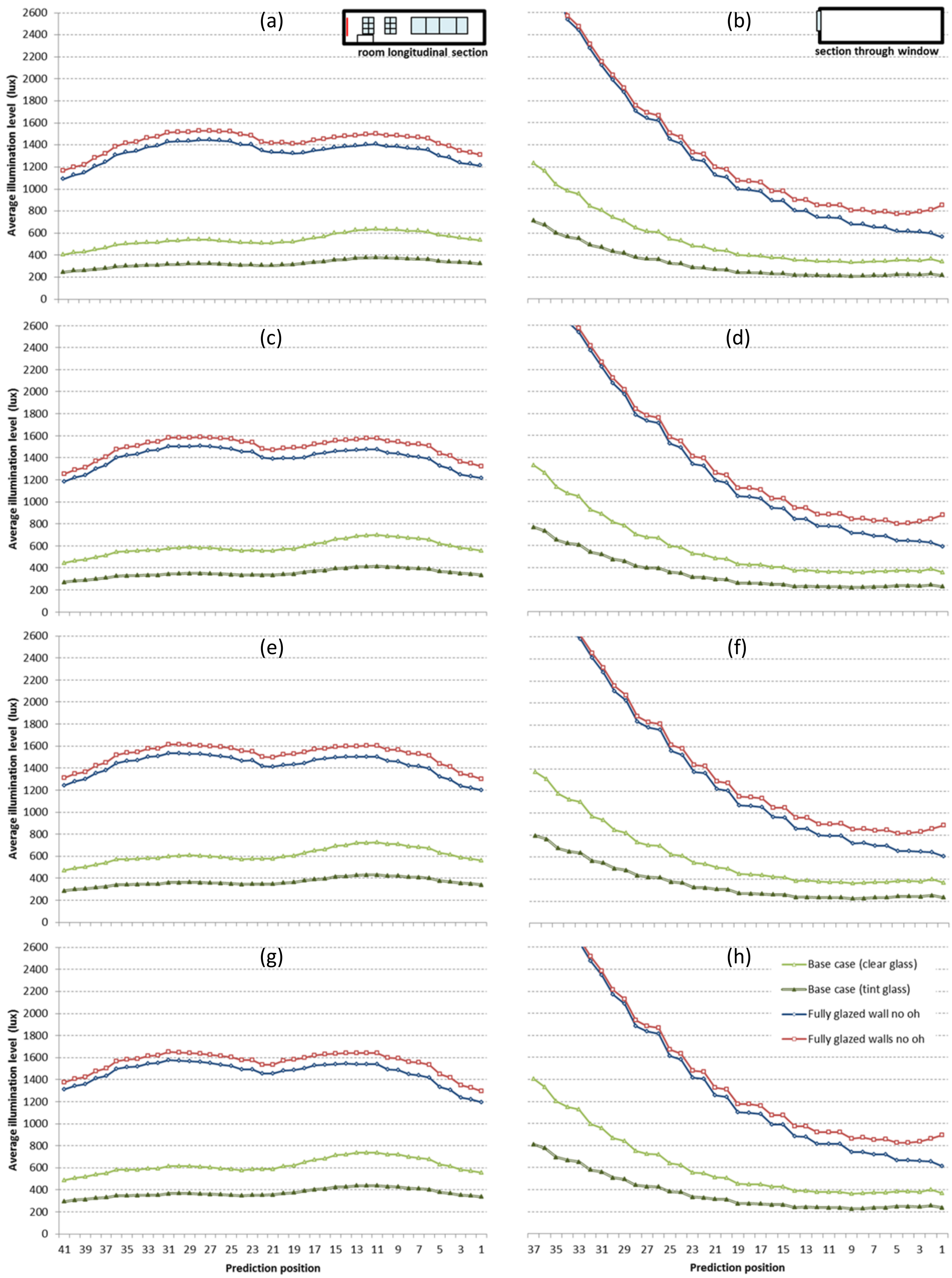


Fig.6. 24 Prediction of average illumination level under sunny clear sky in room 5111 of Sc CRRU on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

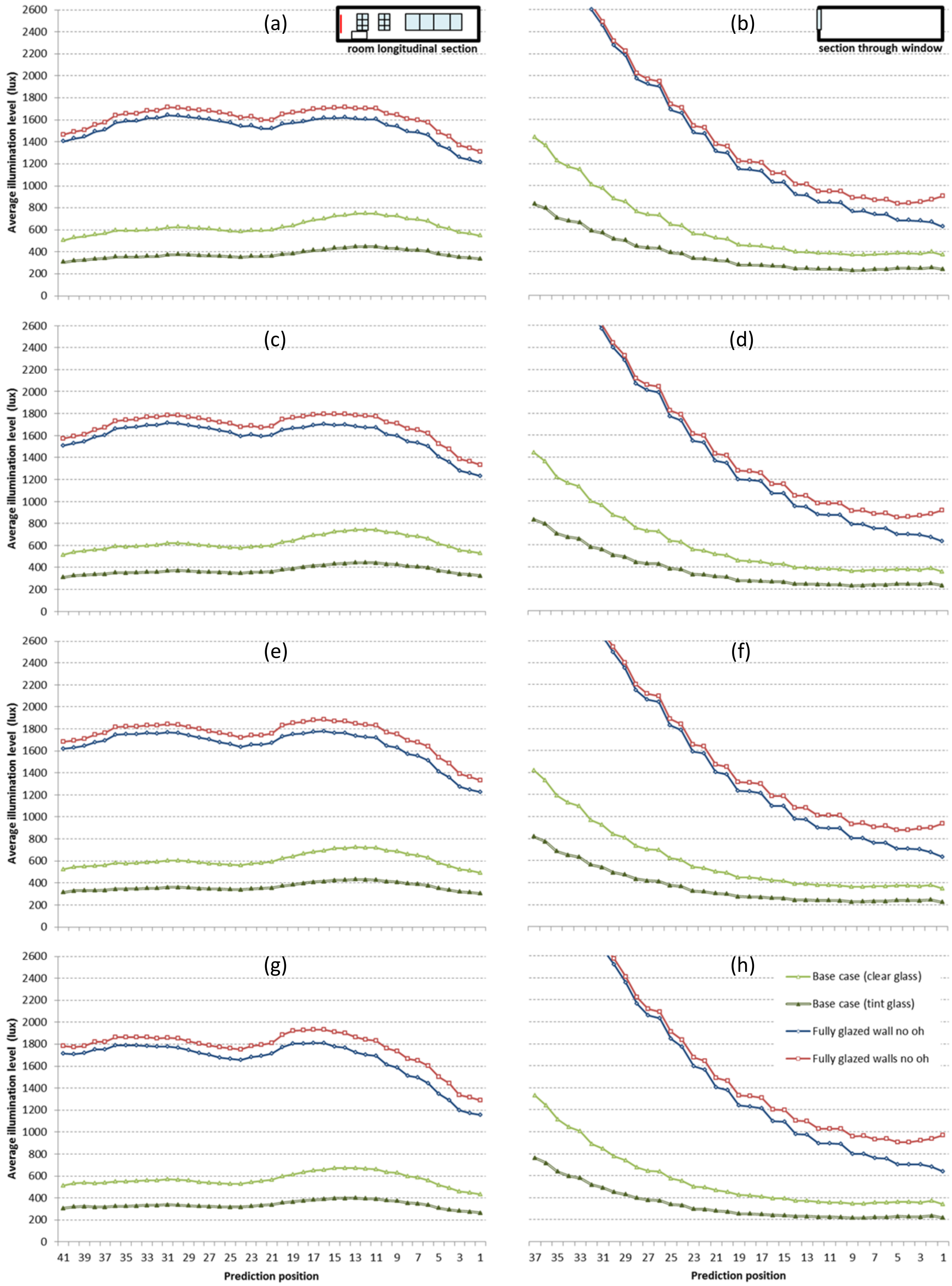


Fig.6. 25 Prediction of average illumination level under sunny clear sky in room 5111 of Sc CRRU on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

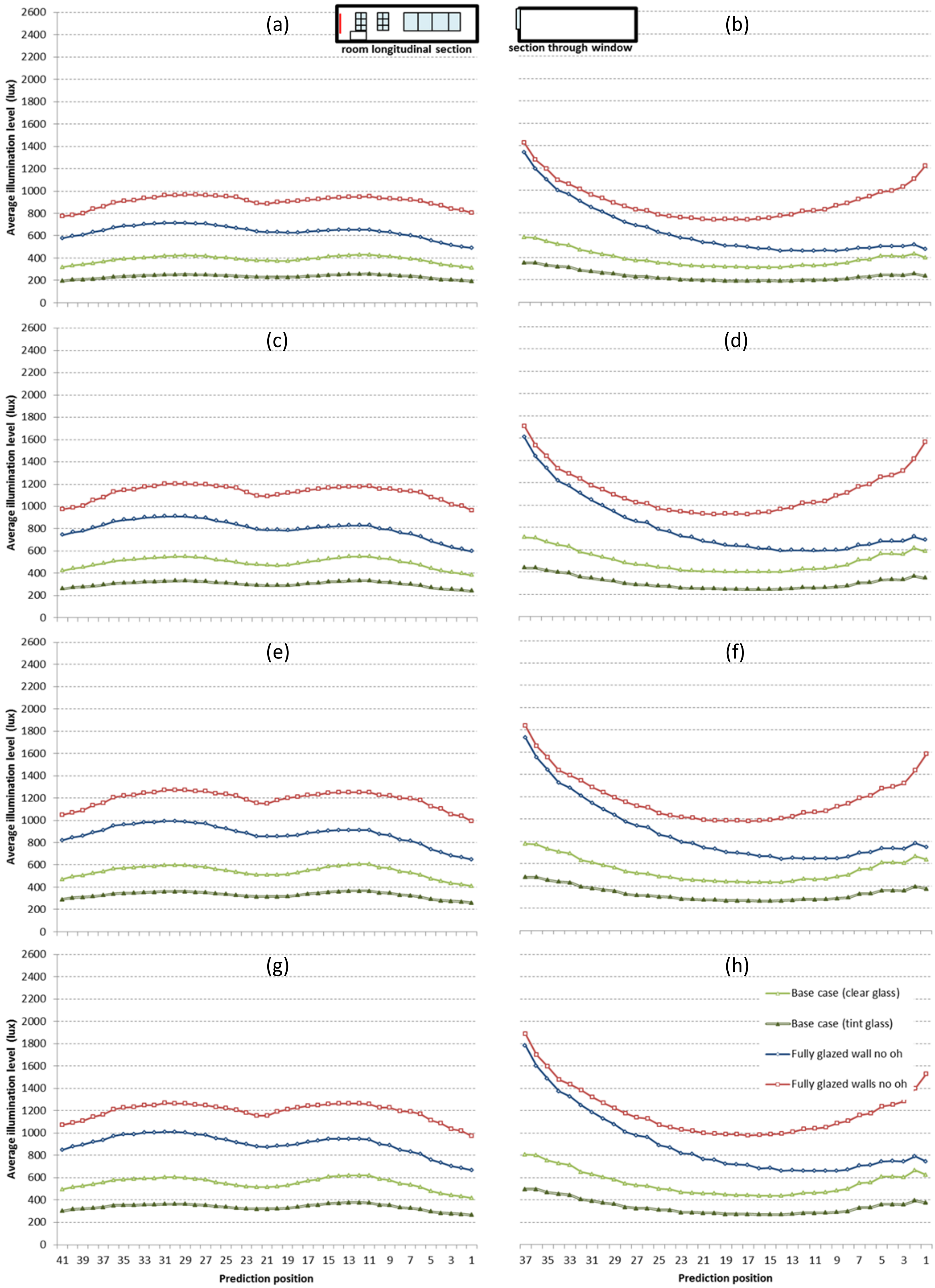


Fig.6. 26 Prediction of average illumination level under sunny clear sky in room 5111 of Sc CRRU on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

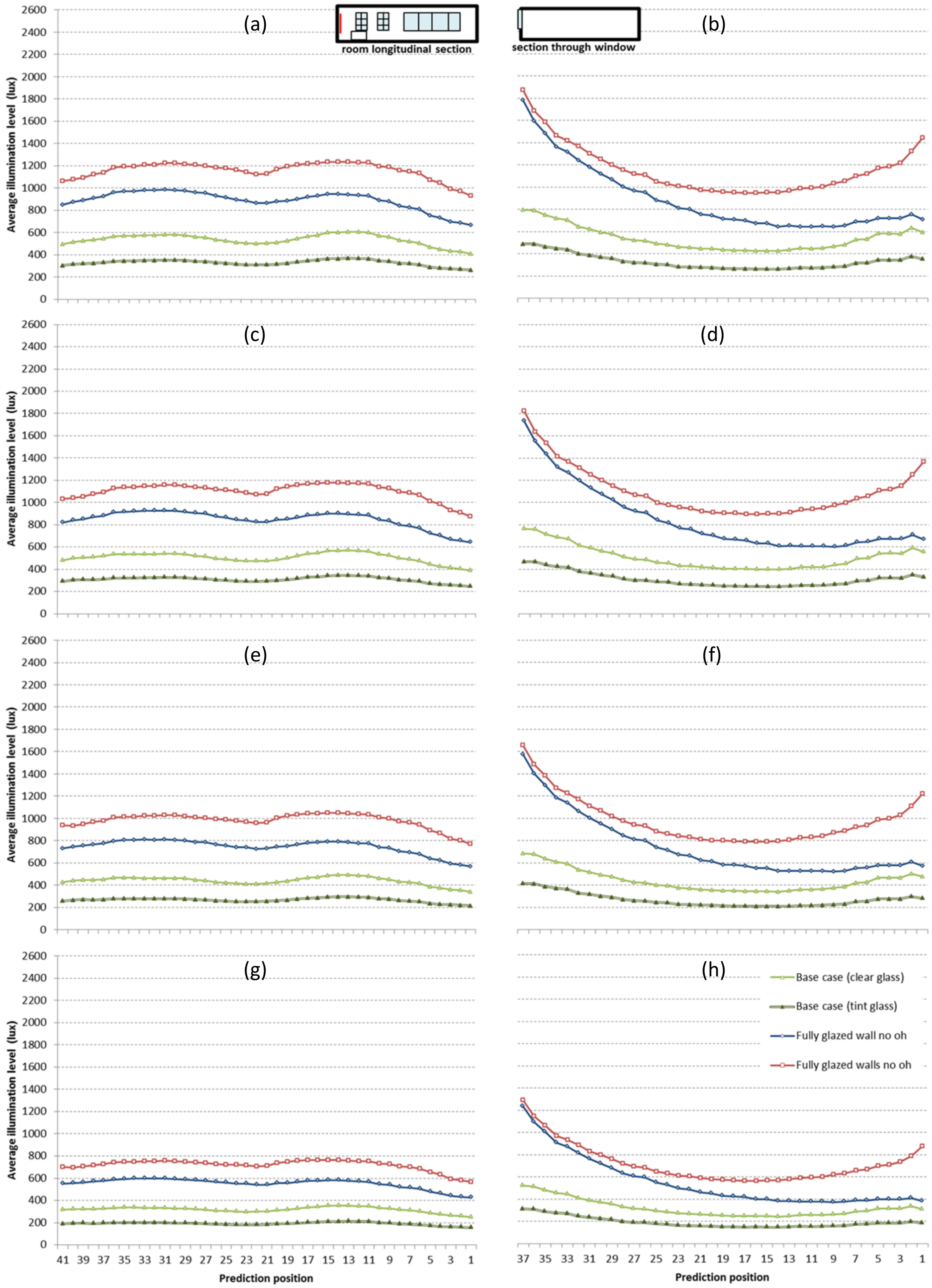


Fig.6. 27 Prediction of average illumination level under sunny clear sky in room 5111 of Sc CRRU on 22nd Dec. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

Because it is the smallest room with two opposite window, illumination levels in room 5111 of Sc CRRU was supposed to be adequate for most of the time, but it was not. The main reason for the problem can be the poor transmittance of the tinted glazing, which was assigned to all windows. When it was replaced by clear glass in the simulation, illumination levels increased by at least about 100 lux and entirely met the standard in summer (see Figure 6.24 and 6.25). It is because the main window of the room 5111 faces to the north, where is influenced by the direct sun in summer. The results in Figure 6.23, 6.26 and 6.27 show that the solution of fully glazed walls can fix daylighting problems for the overcast sky and the winter of clear sky in terms of insufficiency and uniformity. However, the solution may not necessary for the cases of summer which the illumination levels are already adequate. Since 30% of optimization shading depth is suggested for the fully glazed wall, sizes of overhang are considerable large in the other orientations in order to prevent principal effects of direct sun. For the north, the window is slightly influenced by the direct sun requiring no shading device. Applying fully glazed wall without shading device, the simulation reported very poor results in the summer: excessive high illuminance near the window and reduction of illuminance uniformity. It reveals that although the sun affects north orientation in very less frequency, additional requirement about adjustable shading device should be further suggested for effect of indirect daylight from the sky.

d. Room 5406A of PSU

Room 5406A of PSU has similar problem to room 5111 of Sc CRRU in cases of window orientation and use of tint glass. Other specific features of the classroom consist of limited window area and connecting to double loaded corridor.

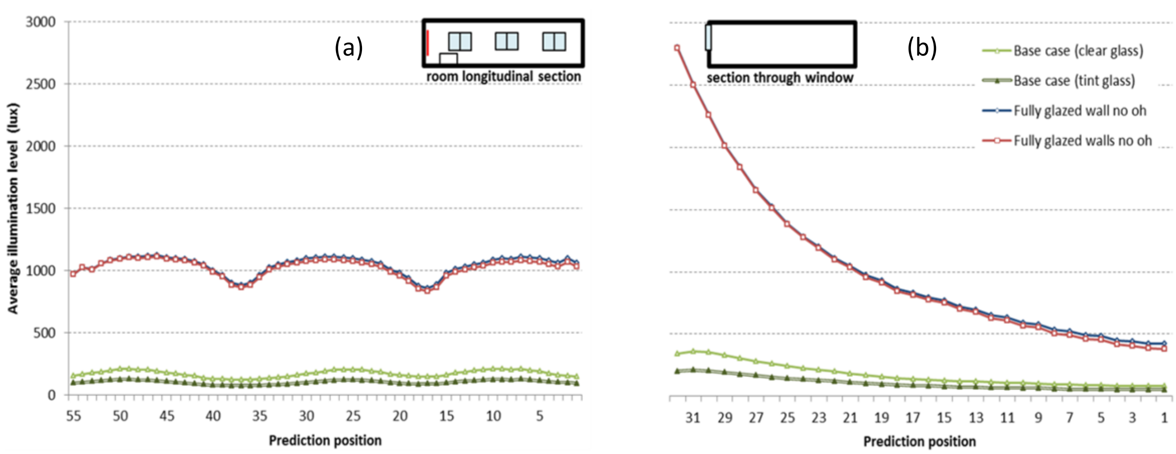


Fig.6. 28 Prediction of average illumination level under overcast sky in room 5406A of PSU. (a) by room longitudinal section and (b) room cross section

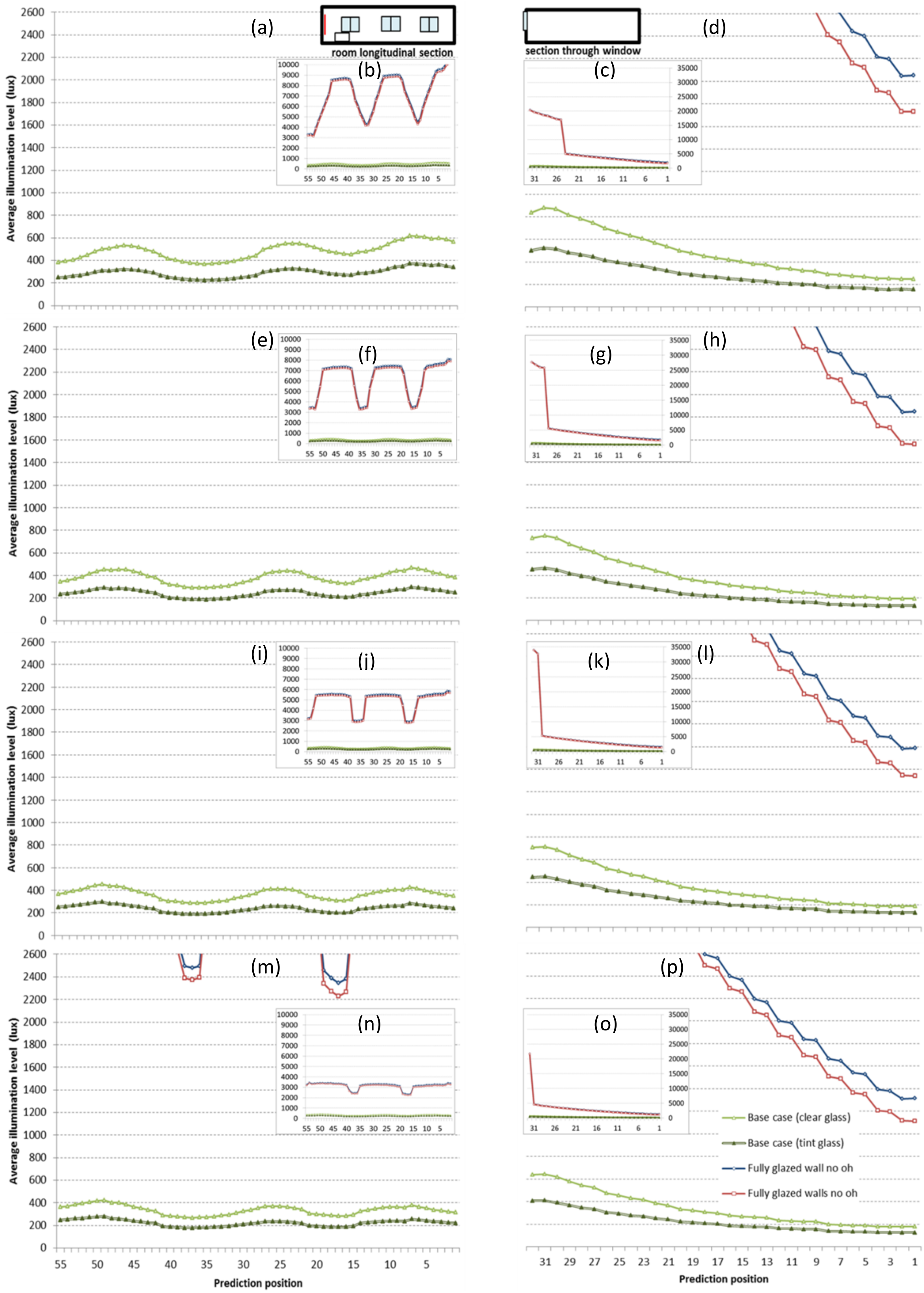


Fig.6. 29 Prediction of average illumination level under sunny clear sky in room 5406A of PSU on 22nd Jun. (a)-(d) 9:00, (e)-(h) 10:00, (i)-(l) 11:00 and (m)-(p) 12:00

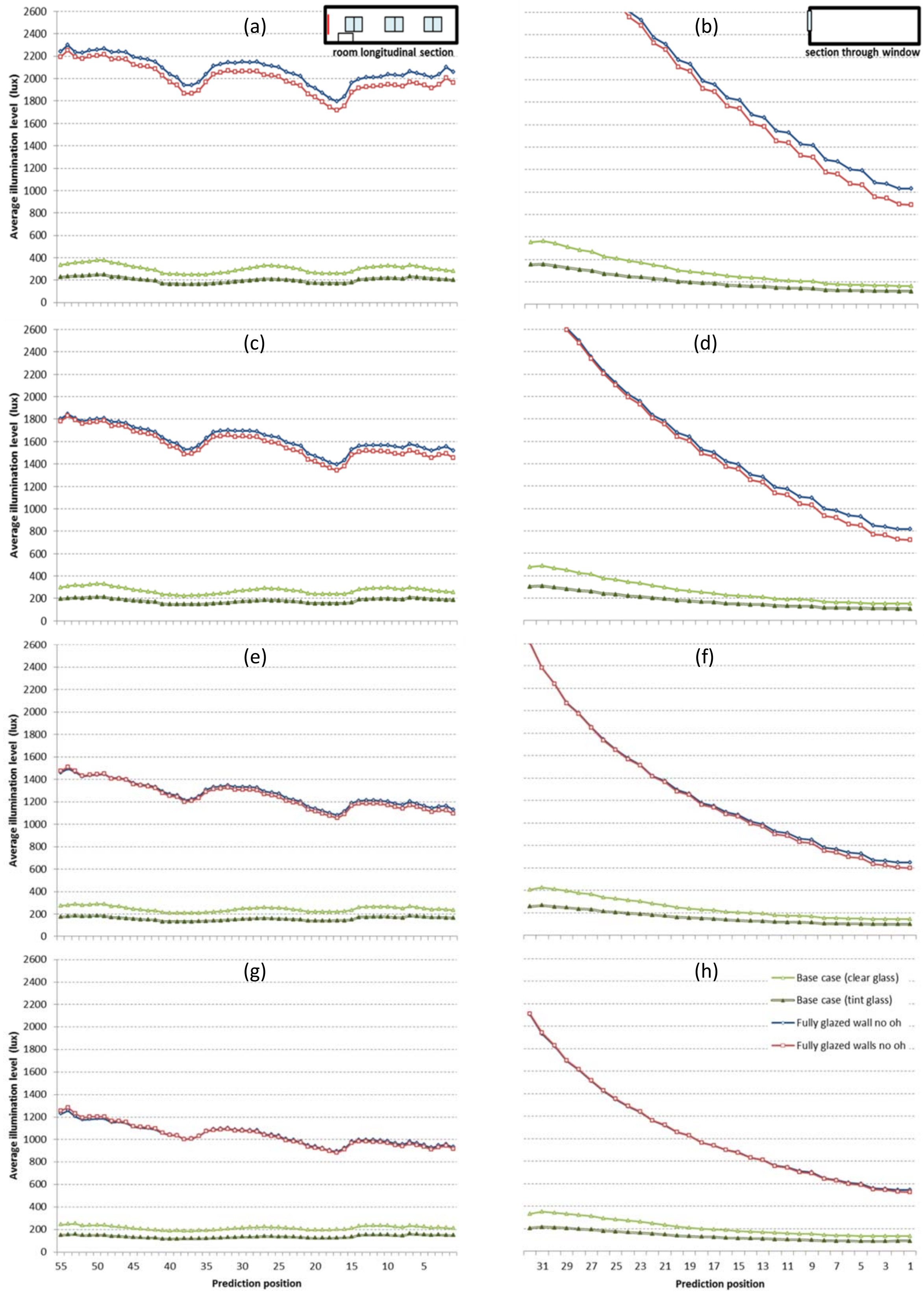


Fig.6. 30 Prediction of average illumination level under sunny clear sky in room 5406A of PSU on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

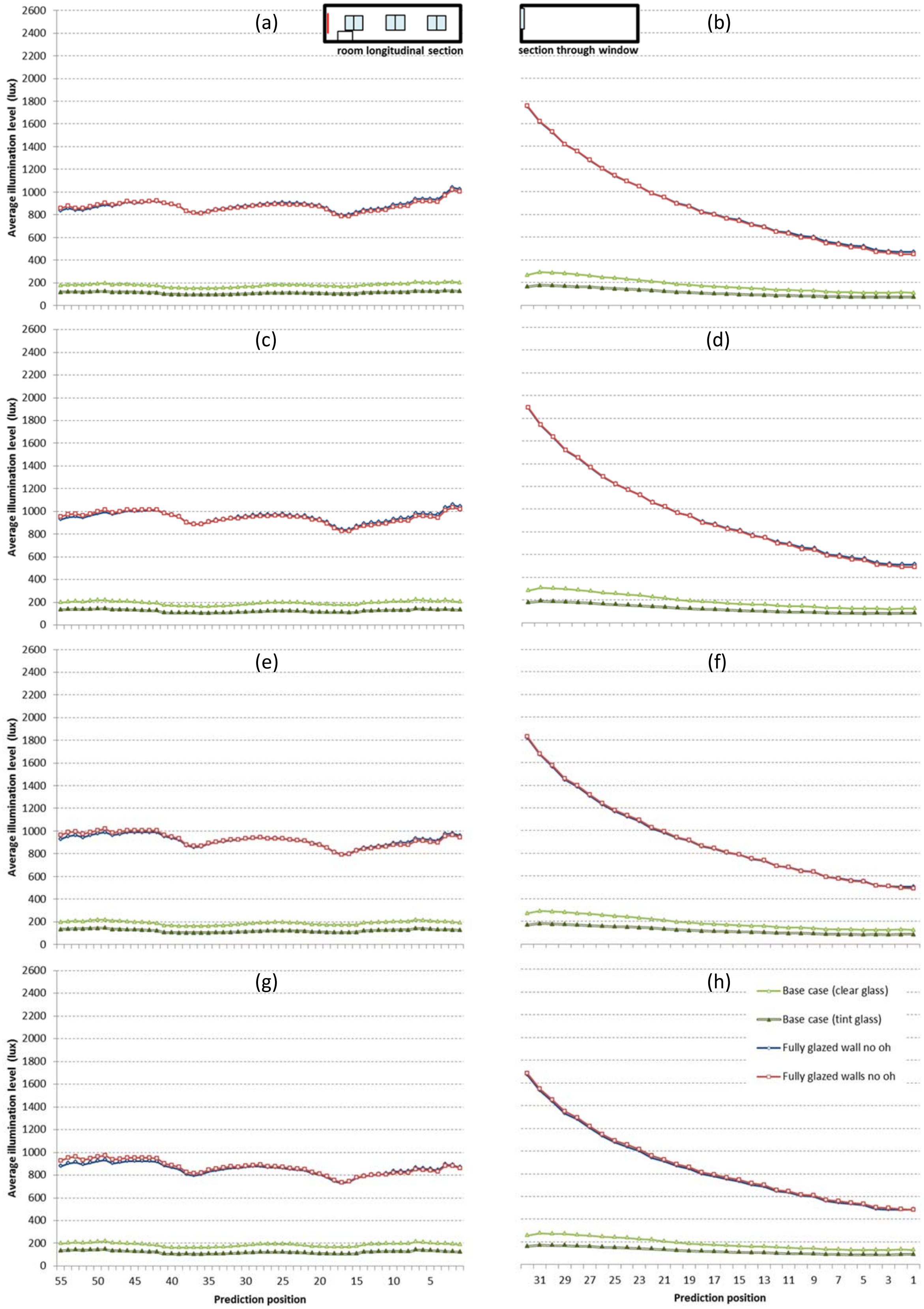


Fig.6. 31 Prediction of average illumination level under sunny clear sky in room 5406A of PSU on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

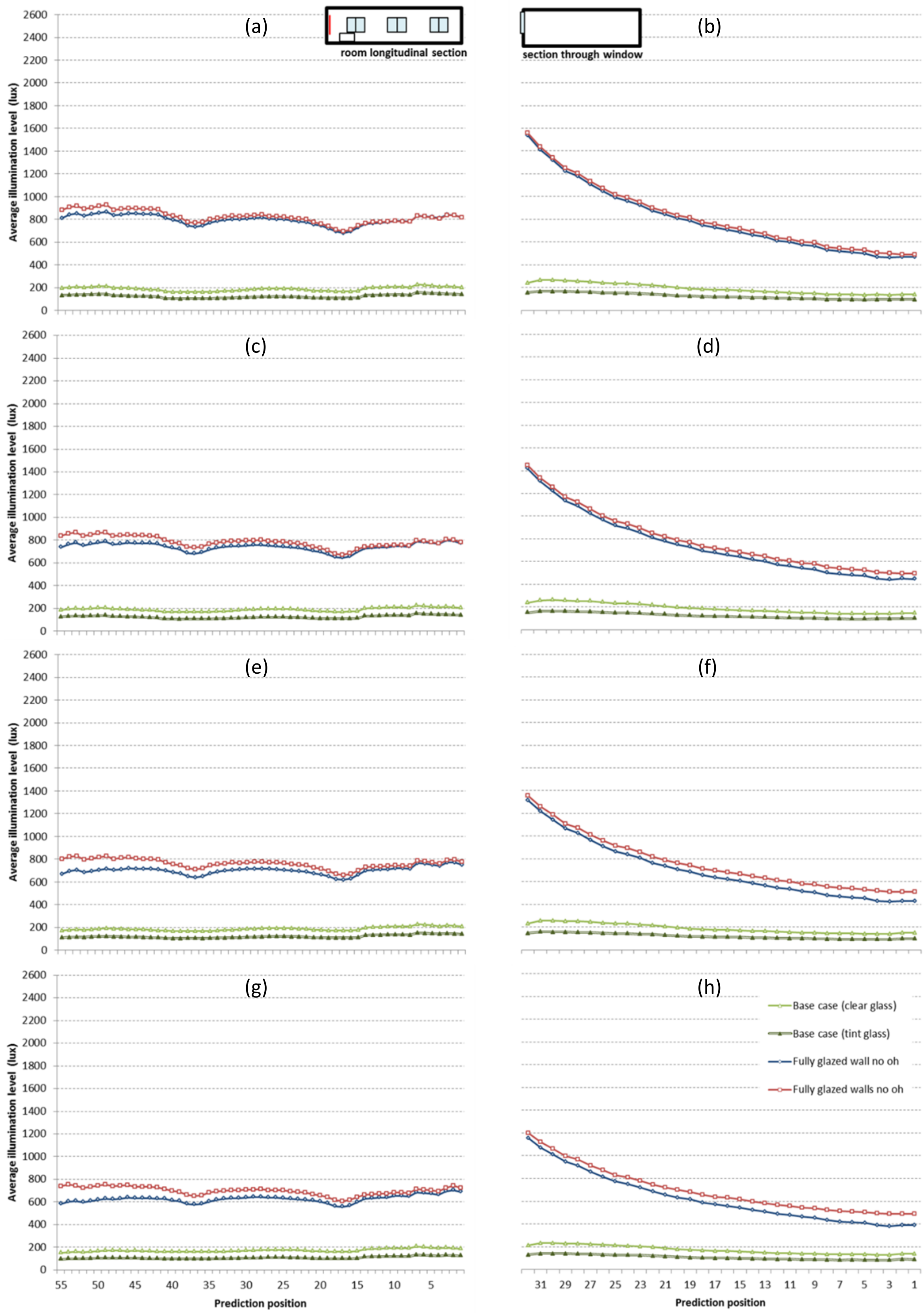


Fig.6. 32 Prediction of average illumination level under sunny clear sky in room 5406A of PSU on 22nd Dec. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

The limited window area is the main reason for insufficient illuminance, especially in the furthest area from the window. The problem might be solved by using a bigger window. As shown in Figure 6.28 - 6.32, the cases of fully glazed walls increased illumination at the furthest area from the window by at least 200 lux. Compared to the room 5111 of Sc CRRU, the room 5406A which is wider is also in standard of illumination level. The occurrence of excessive high illuminance is also the main problem for summer. The solution of two opposite fully glazed walls appears less effect for the room 5406A because it connects to double loaded corridor which only limited daylight was delivered. The enlargement of window connecting to corridor can insignificantly improve the minimal illuminance. It can be concluded that the additional window side may not effective solution for the double loaded corridor classrooms.

2) Conclusion

According to simulation results of additional case studies, the suggested solution can be confirmed in the main case studies context such as south window orientation and the room width of about 10 metres. The solution appears to be useful for other contexts but not in every case. The solution can be directly applied to classrooms with north window orientation, but additional shading is required for the main window in the summer time. For east and west orientations, the width of the room should be small due to less impact of the sun on the window. However, the solution was found less effective for the classroom with double loaded corridor because the daylight hardly transfers into the corridor. Other additional façade design is required for the case that the opposite side window cannot be included.

6.3 Reflecting strategies

It is interesting to enhance daylighting for single sidelighting, although a double loaded corridor is not generally used in tropical classrooms. It is because passive strategies such as daylighting and natural ventilation are substantially essential for most of public zone and circulation in non-commercial building types like educational buildings. However, due to the design limitations of some buildings, single sidelighting is compulsory. Results in Chapter 5 imply that the additional corridor window is the only parameter which can improve illumination uniformity. As the additional parameter to solve weaknesses of single sidelighting, the reflecting strategy may not relate to thermal aspect, but it is the most effective parameter in terms of daylighting. According to review of reflecting strategy in chapter 2, reflecting elements probably fix single sidelighting problems. Therefore, the strategy is included in the application part of this research.

Reflecting elements have been broadly recommended for façade design for daylighting, mostly in temperate climate areas. Moreover, the effectiveness of the device was confirmed in previous studies in some of subtropical climates (e.g. Ho et. al., 2008). Apart from the devices, it is recommended to have the highest reflectance, few obstacle and low reflecting plane are also required. The alternatives of reflecting elements were selected to investigate impact of reflecting strategy on illumination uniformity of single sidelighting. The focused feature of the device is simple combination of overhang and light shelves. The application of other forms of the device was found in previous studies that not only need to be integrated to other room elements such as ceiling form but the directional reflection from some focused curved devices also too complicate to be generalise in different sun geometry.

The fact that the shading requirement of the device depends on window size results in separate study for the existing window and the fully glazed wall case. Impact of the device reflectance will be presented in the last part of this session.

1) Façade improvement for existing window

The existing façade, which approximates to the recommendation, appears too large when light shelves were combined with the façade. The other cases were selected using information from previous studies about effectiveness of the top and the low light shelves. The sizes of the devices depend on the suggested shading depth: 30% of optimized shading device. As a result, the 'Base case with ls' means the classroom with existing window, 0.45 metre deep overhang and 0.9 metre top light shelf which located 0.6 metre under the overhang. The 'Base case with ls & lls' bases of the 'Base case with ls' in size which 0.9 metre low light shelf was included. The façade appearances show as sections in Fig.6. 33. The reflectance of all cases is 70%.

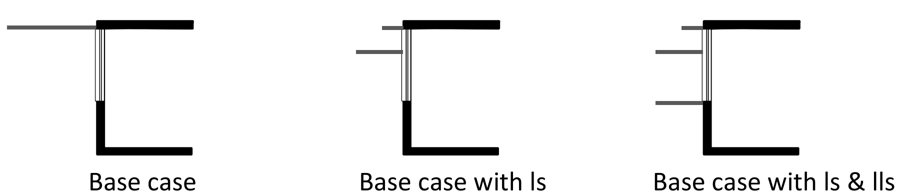


Fig.6. 33 Sections of three façade types which were applied to existing window in the simulation.

Comparing to the base case, the light shelf cases supposed to improve daylighting quantity especially in the furthest area from window and the results shown in Figure 6.34 – 6.38 also support this idea.

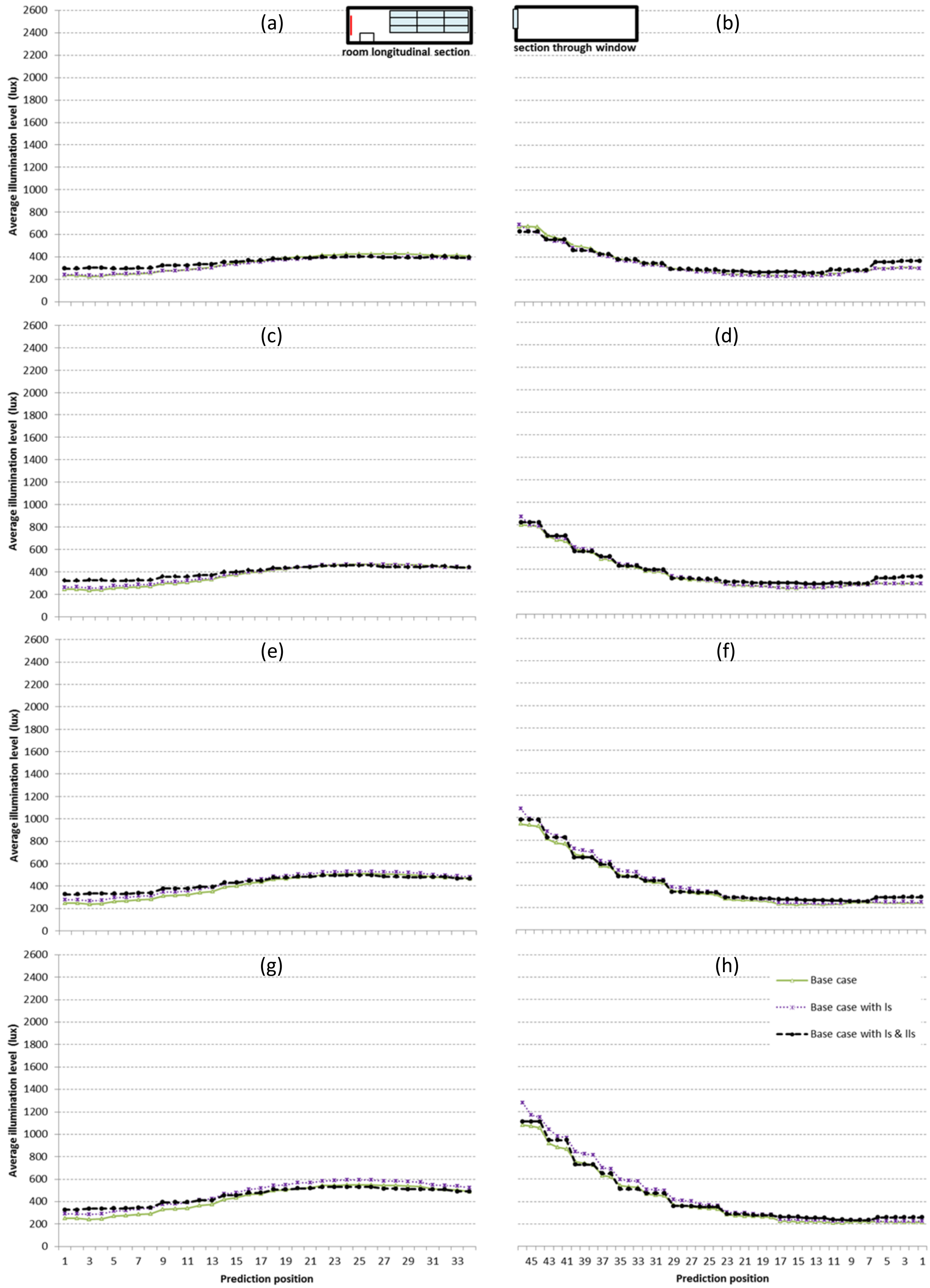


Fig.6. 34 Effect of light shelf on average illumination level under sunny clear sky on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

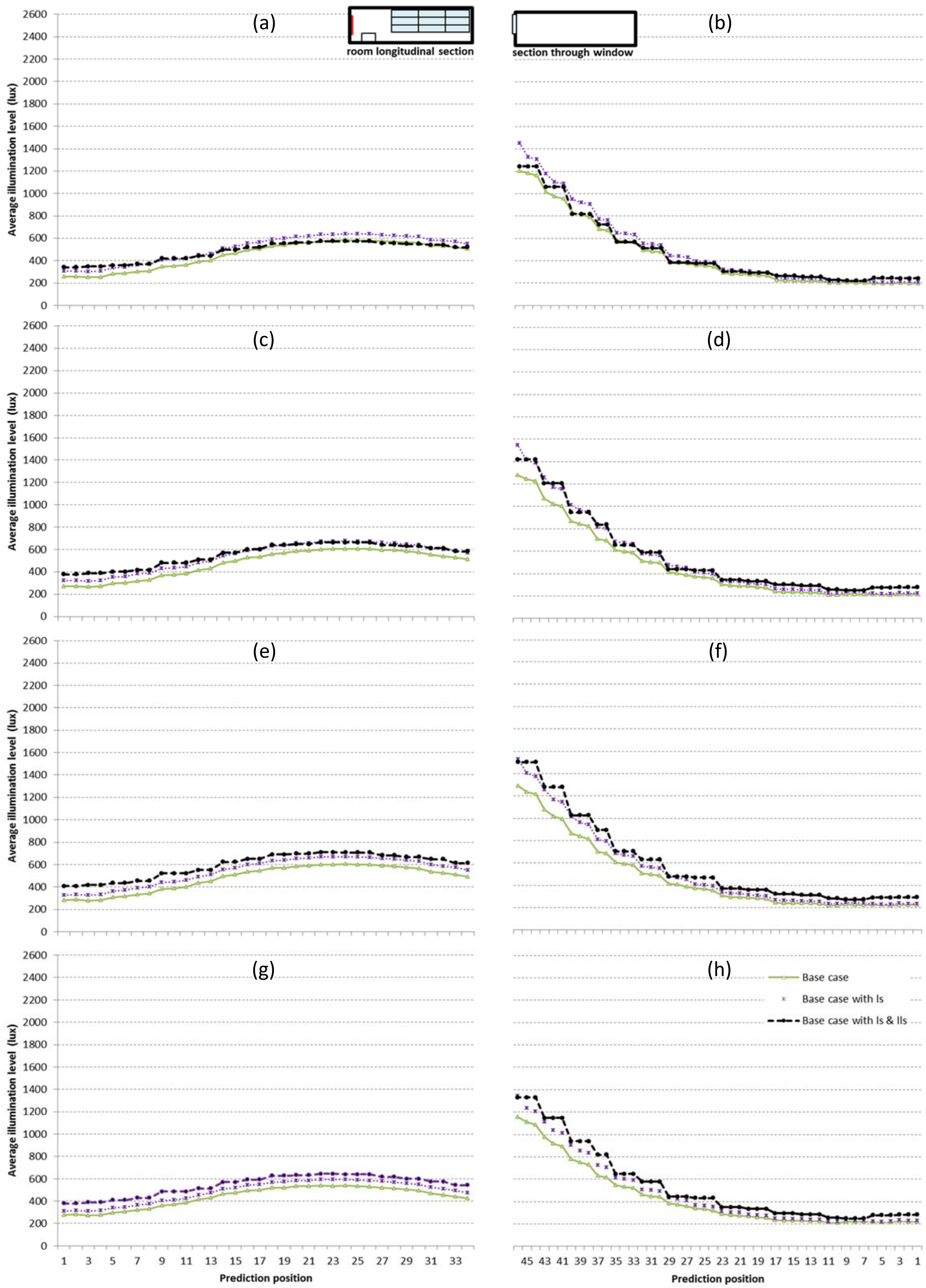


Fig.6. 35 Effect of light shelf on average illumination level under sunny clear sky on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

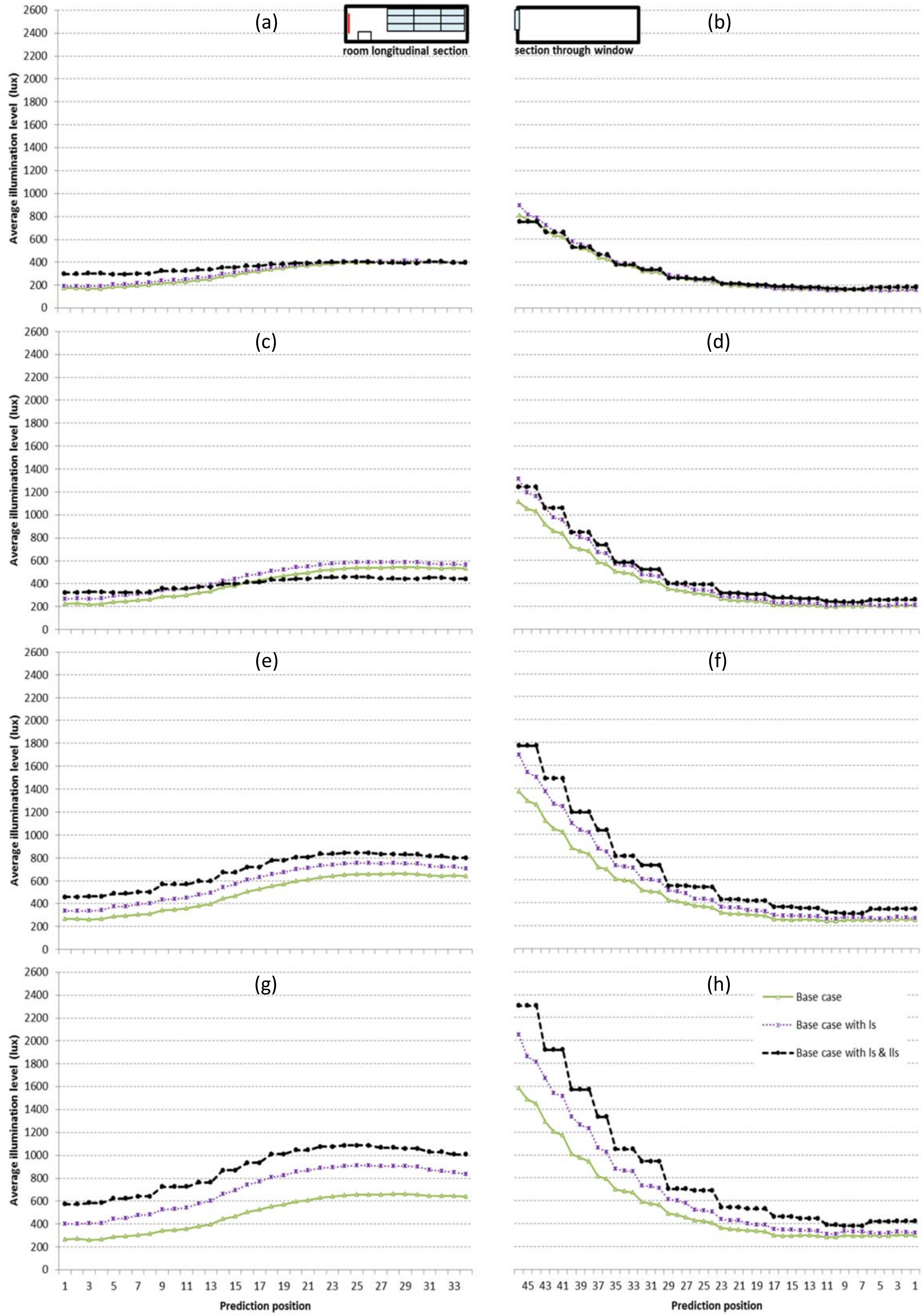


Fig.6. 36 Effect of light shelf on average illumination level under sunny clear sky on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

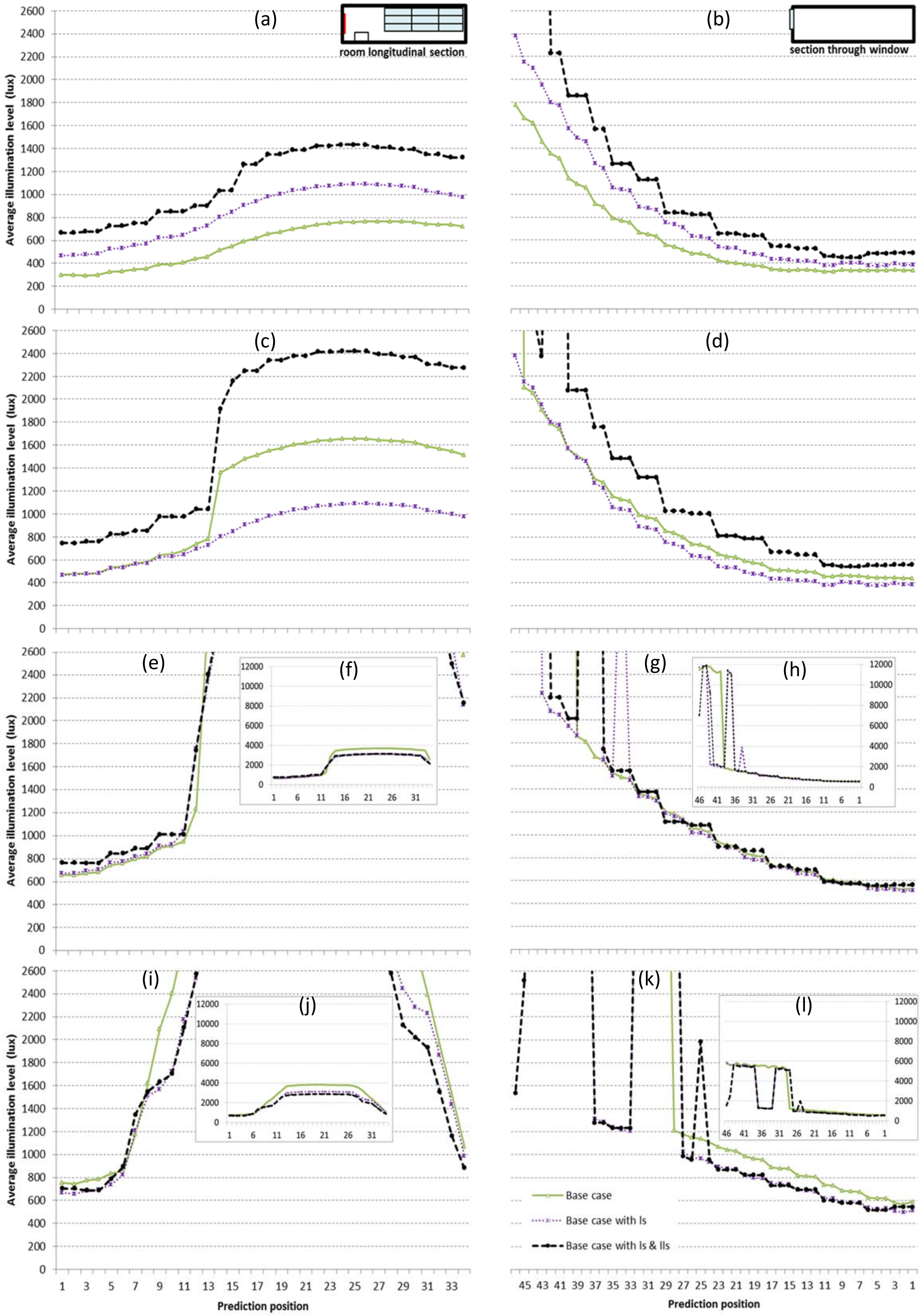


Fig.6. 37 Effect of light shelf on average illumination level under sunny clear sky on 22nd Dec. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(h) 15:00 and (i)-(l) 16:00

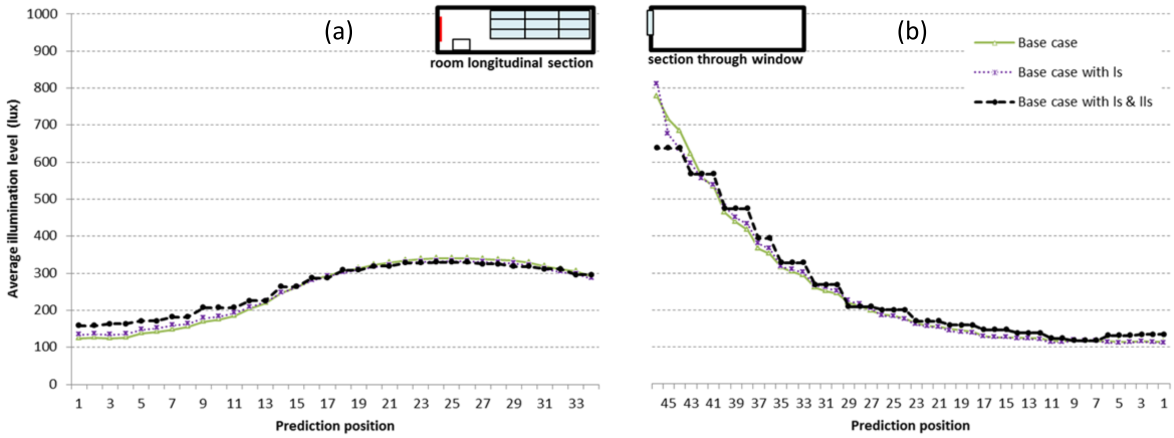


Fig.6. 38 Effect of light shelf on average illumination level under overcast sky (a) by room longitudinal section and (b) room cross section

The case with high and low light shelves may provide better results than the case with a high light shelf and the base case respectively but the differences are very insignificant in general. The most effective time for the device is between 12PM to 2 PM when the minimum illumination levels were improved by about 100-200 lux. It can partly confirm the impact of low angle sun on the device. However, light shelf cases at 3PM and 4PM which supported to be influenced by the low angle sun rather have very poor results. It might be because the low angle sun at those specific times provides lower illumination level than that at the time from 12PM to 2PM. Moreover, the light shelf reflection of 3PM and 4PM is in diagonal directions (shown in Figure 5.15) which provide less effect than the straight direction. However, the graphs in Figure 6.37 (e)-(l) demonstrate the effect of direct sun on the working plane for all cases. The light shelf cases appear to be better than base case in terms of shading although there is insignificant different illuminance at the furthest area from window.

2) Reflecting façade for fully glazed wall

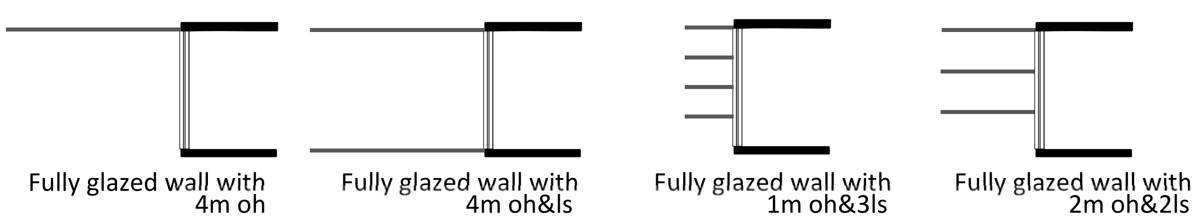


Fig.6. 39 Sections of four façade types which were applied to fully glazed wall in the simulation.

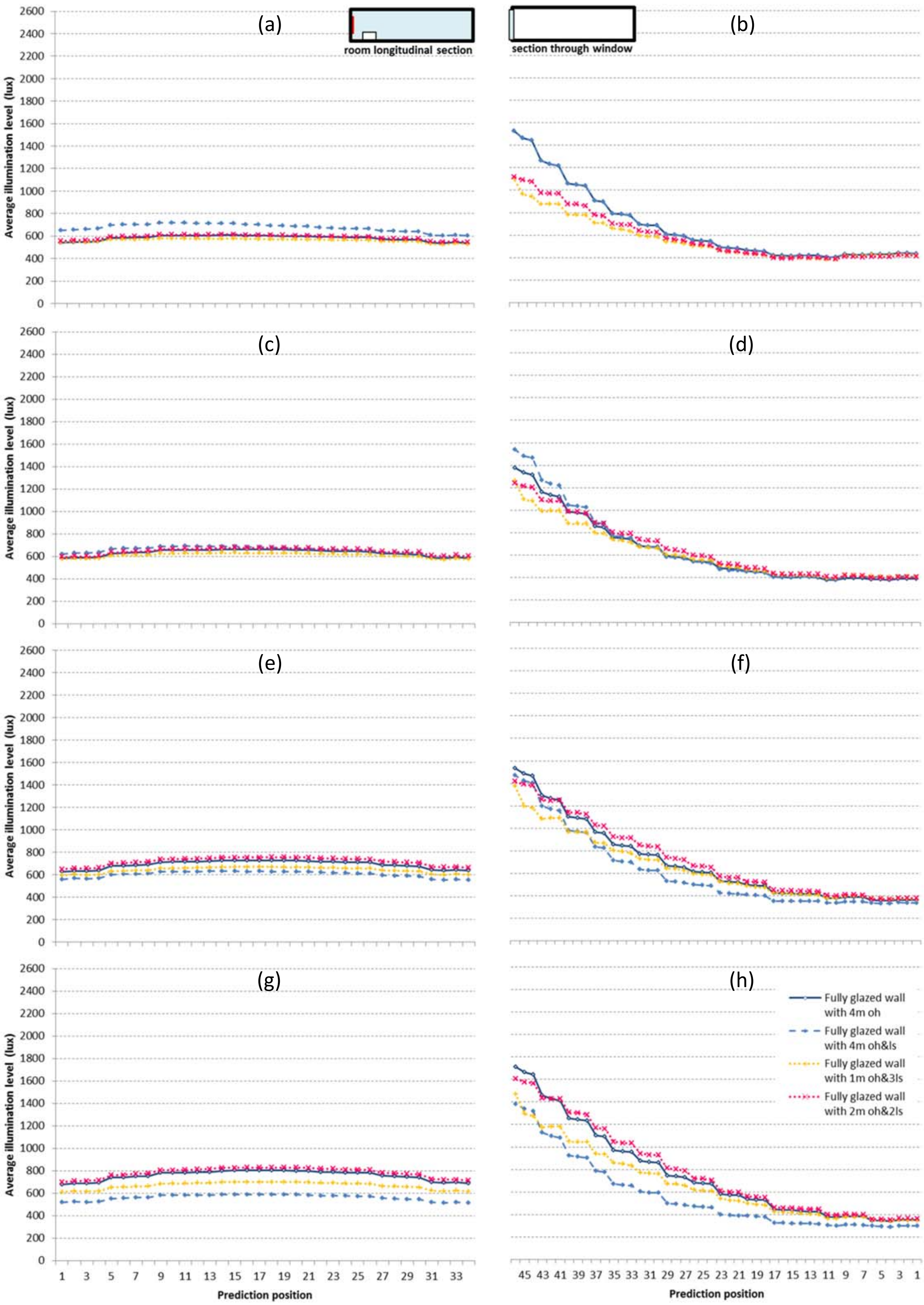
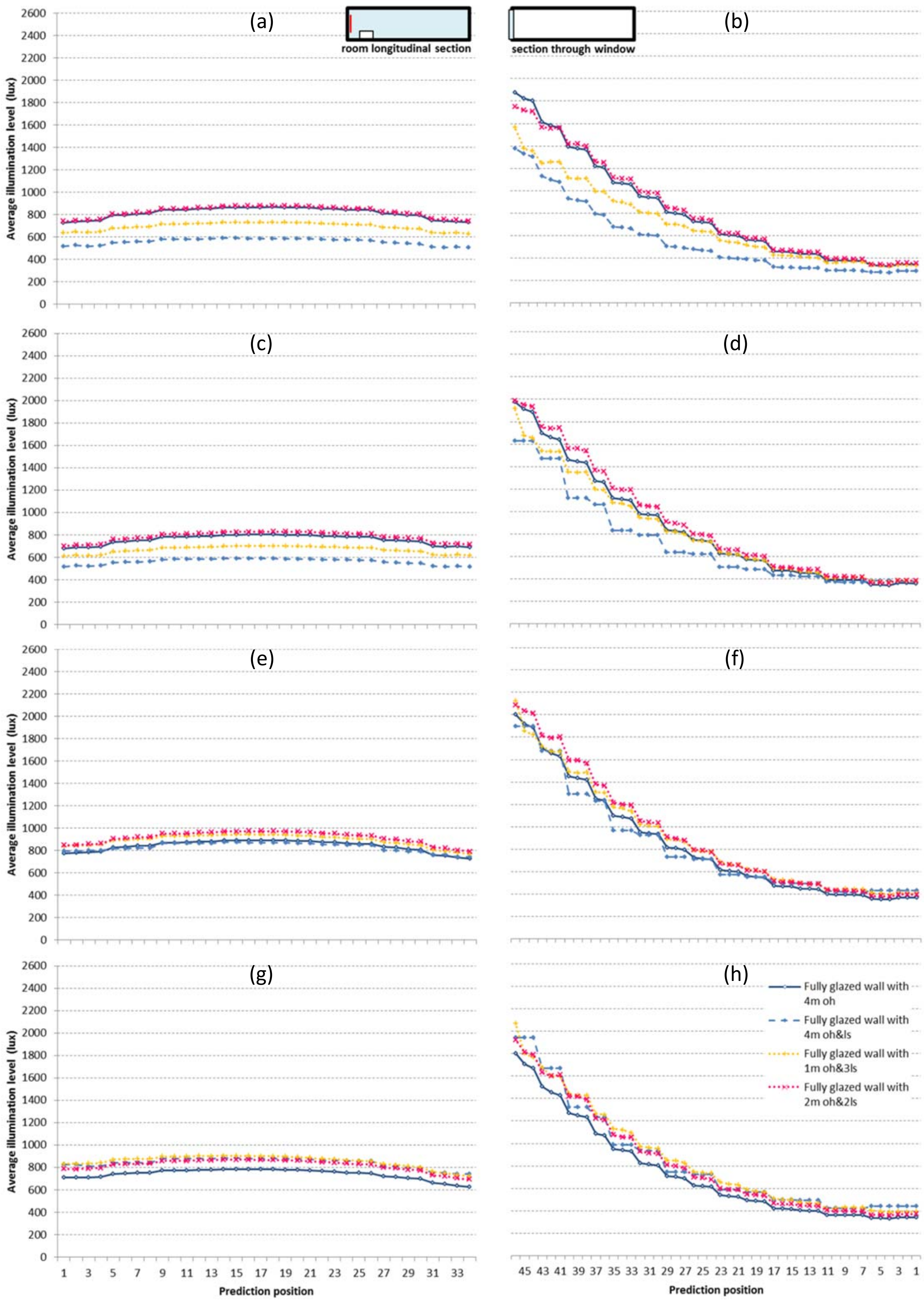


Fig.6. 40 Comparison of average illumination level in four different façade features under sunny clear sky on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00



Fiig.6. 41 Comparison of average illumination level in four different façade features under sunny clear sky on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

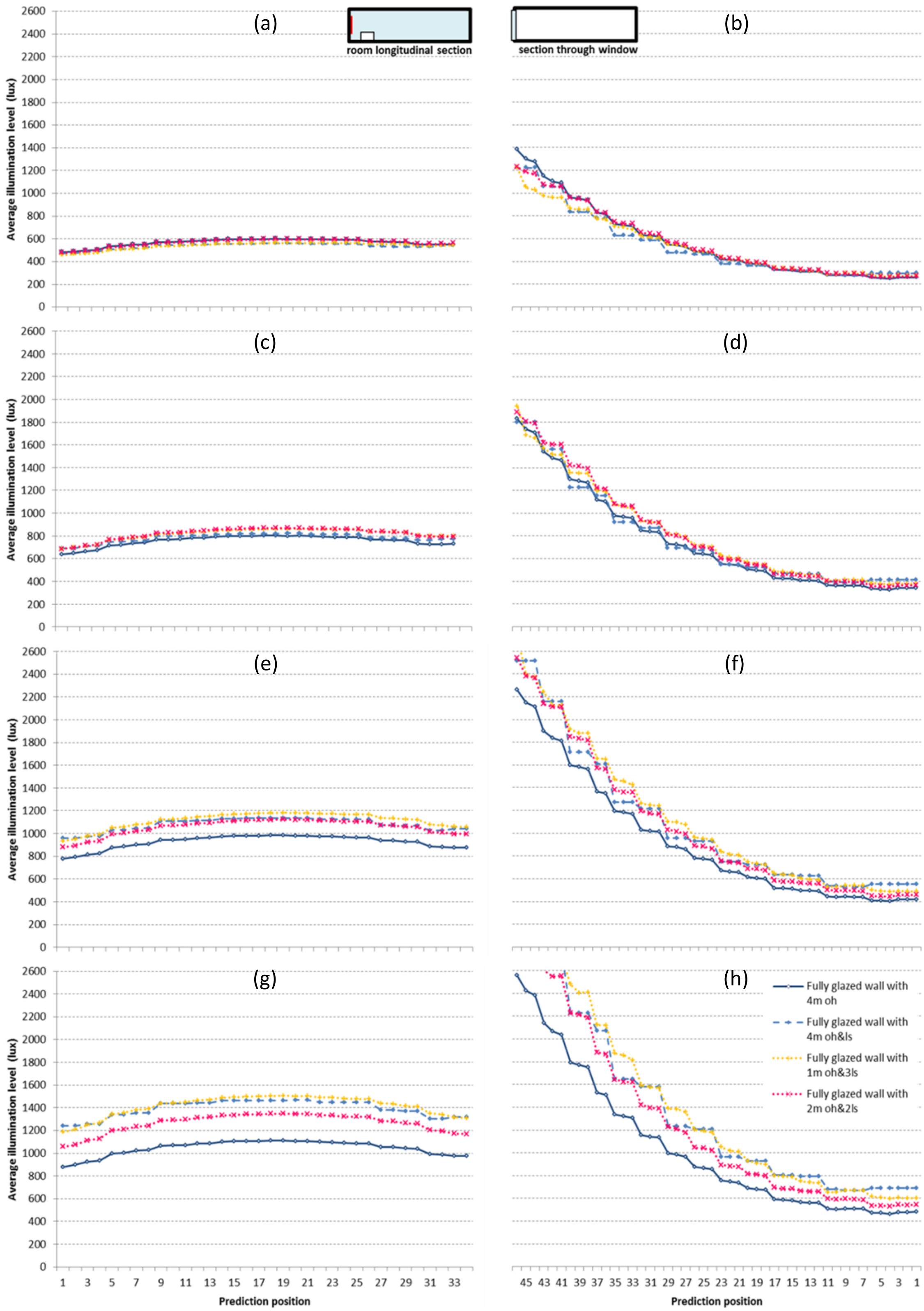


Fig.6. 42 Comparison of average illumination level in four different façade features under sunny clear sky on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

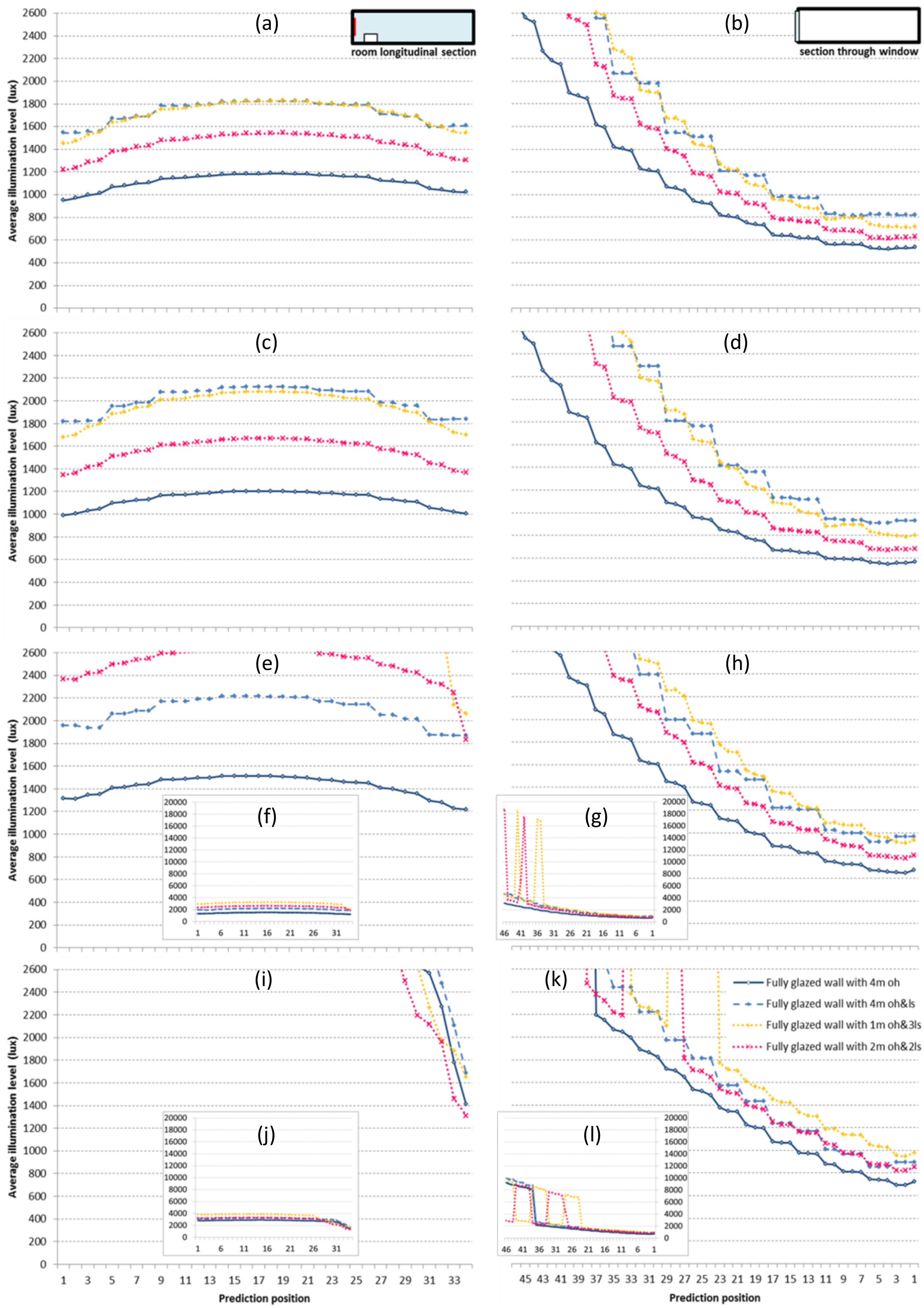


Fig.6. 43 Comparison of average illumination level in four different façade features under sunny clear sky on 22nd Dec. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(h) 15:00 and (i)-(l) 16:00

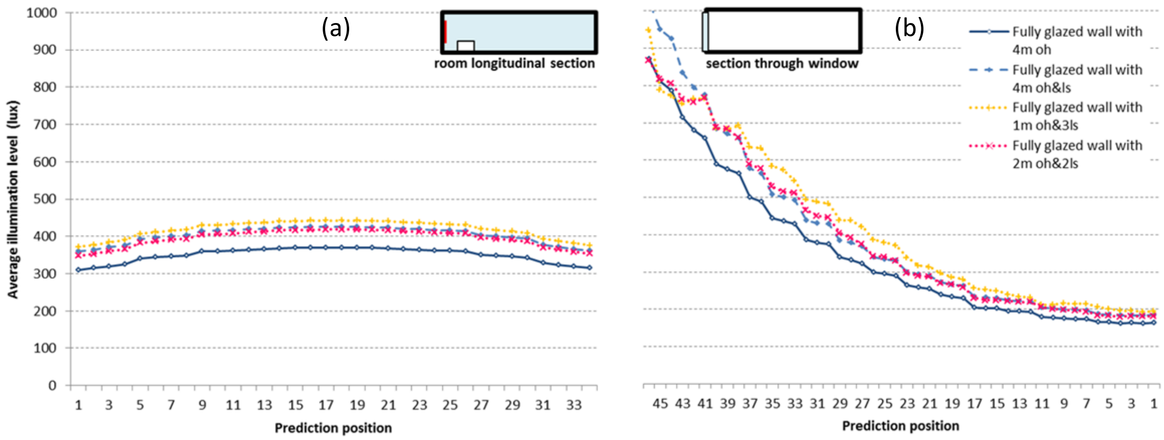


Fig.6. 44 Comparison of average illumination level in four different façade features on under overcast sky (a) by room longitudinal section and (b) room cross section

For a better understanding of the effect of reflection elements, different types of light shelf were investigated by instigating them with fully glazed wall in order to study most possible advantage of the device. The selected cases shown in Figure 6.39 result from issues that are questioned from inconsistent results of previous studies.

The size and distance between horizontal blades were focused in this set of simulations. Comparing to the suggested overhang size, the reflecting elements are assigned in different sizes and distances. There are totally four cases: 'fully glazed wall with 4 m oh', 'fully glazed wall with 4 m oh&ls', 'fully glazed wall with 1 m oh&3ls' and 'fully glazed wall with 2 m oh&3ls'. The 'fully glazed wall with 4 m oh&ls' contains four metre horizontal planes at the top and bottom of the window. When the window was equally divided by horizontal blades, the 'fully glazed wall with 1 m oh&3ls' and 'fully glazed wall with 2 m oh&3ls' consisted of four blades in the size of one metre depth and three blades in the size of two metre depth respectively.

Figures 6.40 – 6.44 can support insignificant effect of light shelf in most case and most affective time for using reflecting elements. The 4 metre light shelf case generally performs best result for improving minimum illuminance for about maximally 400 lux in the furthest area from the window excepting the cases with effect of low angle sun at 3PM and 4 PM of 22nd of December. At those times, the case of 'fully glazed wall with 1 m oh&3ls' provided better results for the dimmest area of the room. The 'fully glazed wall with 2 m oh&3ls' provides either poorer or similar results to the others. The results reveal importance of light shelf size. The large light shelf at the window bottom only advantages illumination improvement while the multiple light shelves can be both reflector and obstacle. The larger obstacle results in the more reduction of illuminance. Furthermore, the smaller blades also allow direct sun penetration deeper than the bigger one.

3) Reflectance of the device

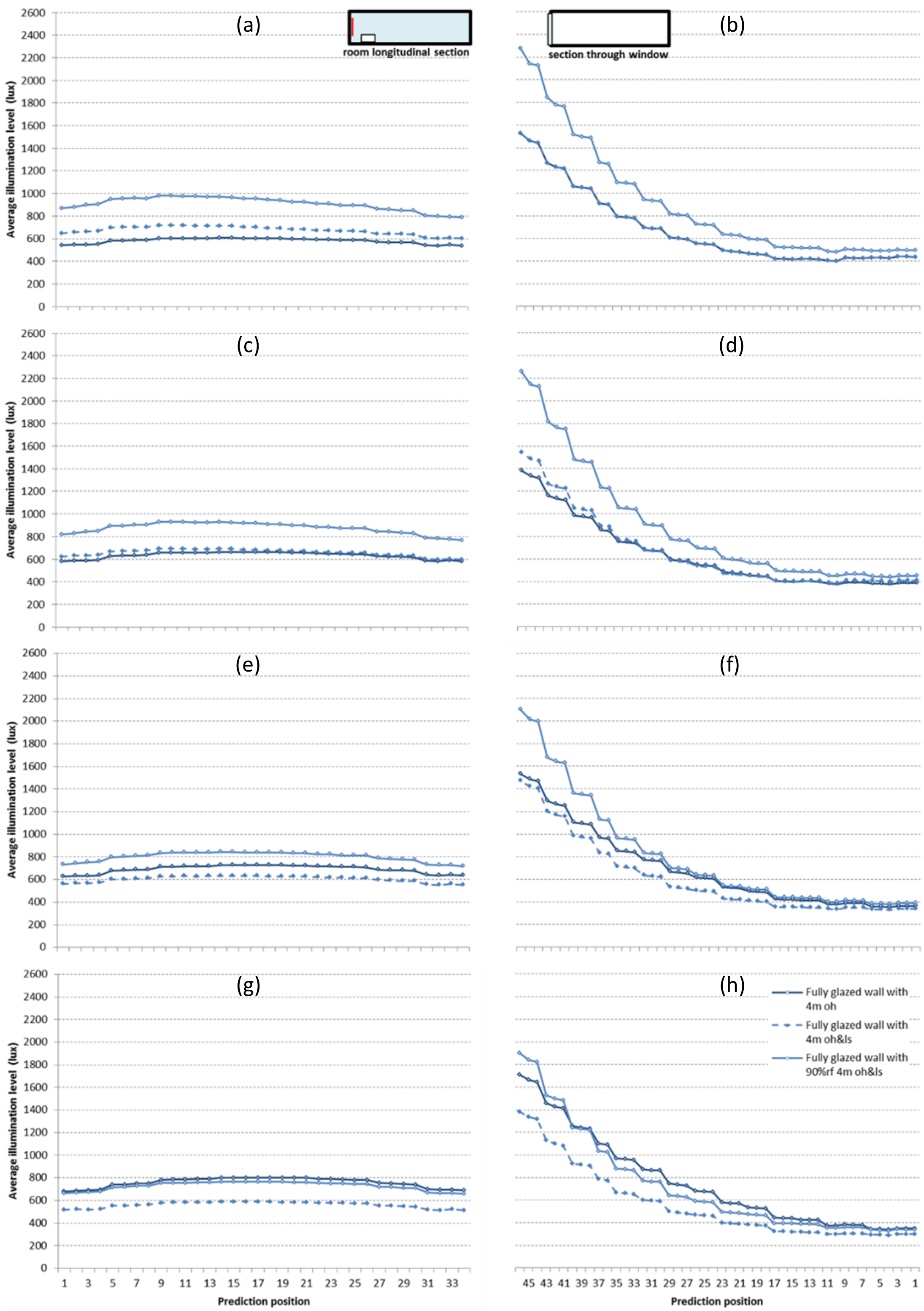


Fig.6. 45 Effect of light shelf reflectance on average illumination level under sunny clear sky on 22nd Jun. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

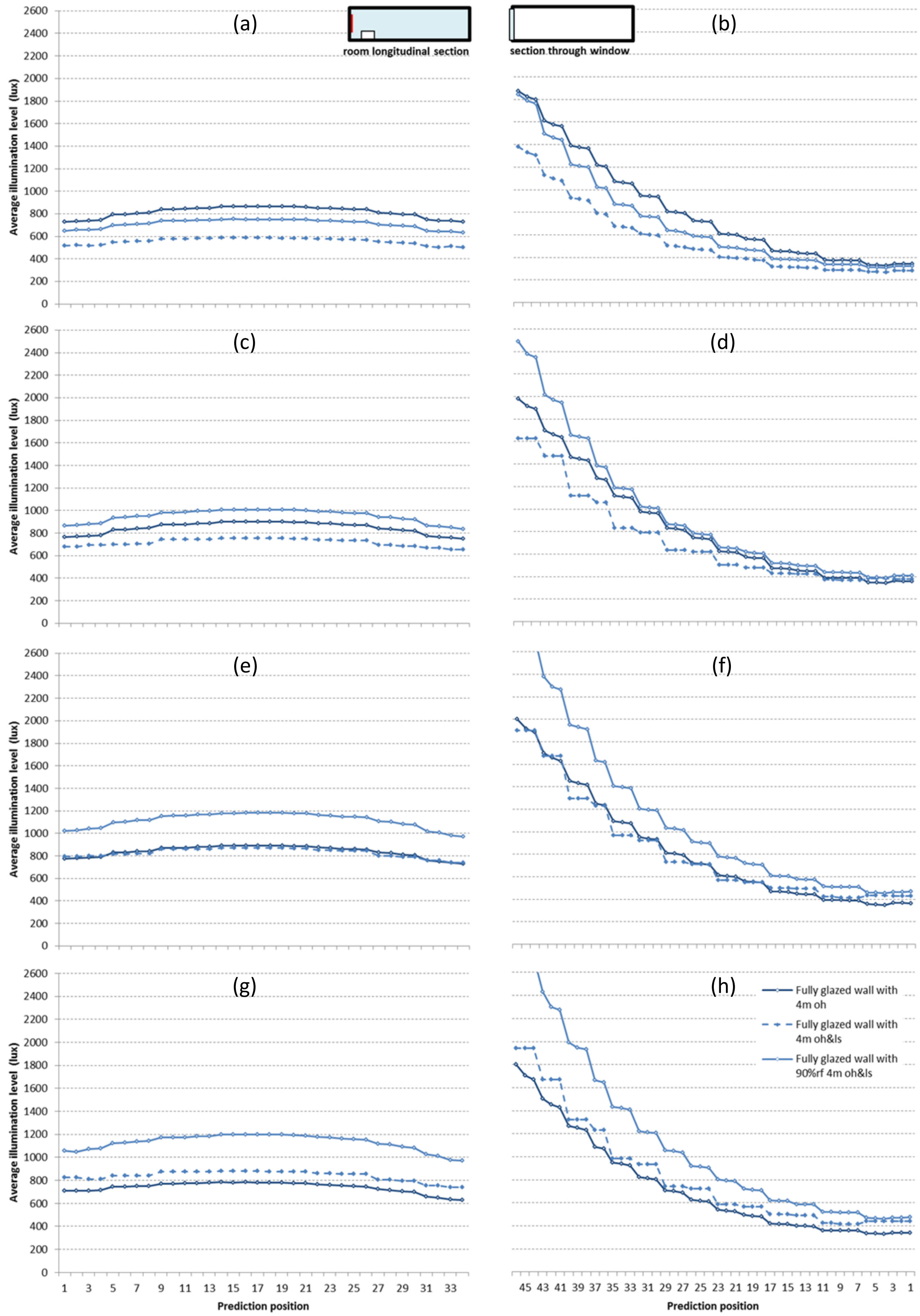


Fig.6. 46 Effect of light shelf reflectance on average illumination level under sunny clear sky on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(h) 16:00

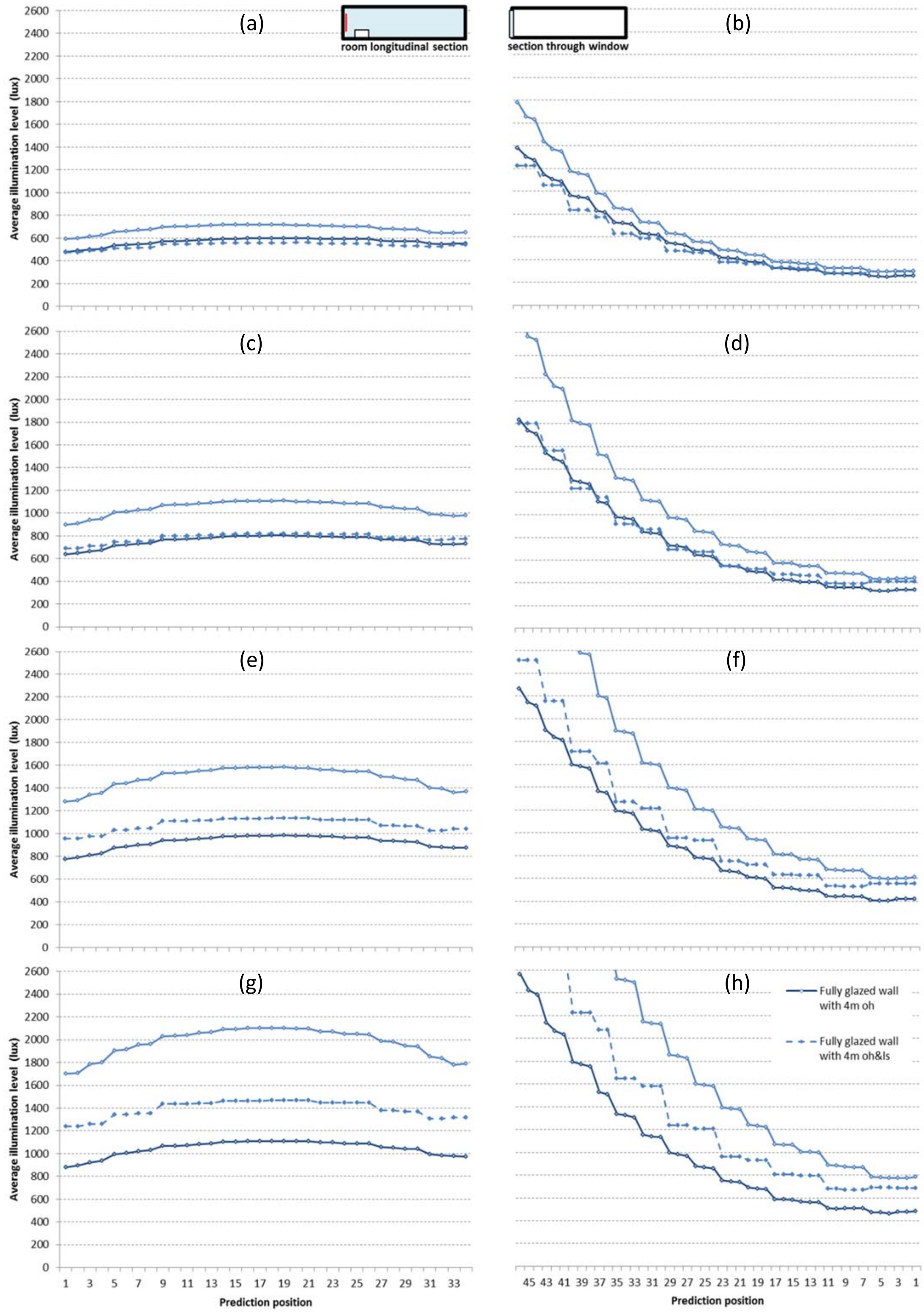


Fig.6. 47 Effect of light shelf reflectance on average illumination level under sunny clear sky on 22nd Dec. (a)-(b) 9:00, (c)-(d) 10:00, (e)-(f) 11:00 and (g)-(h) 12:00

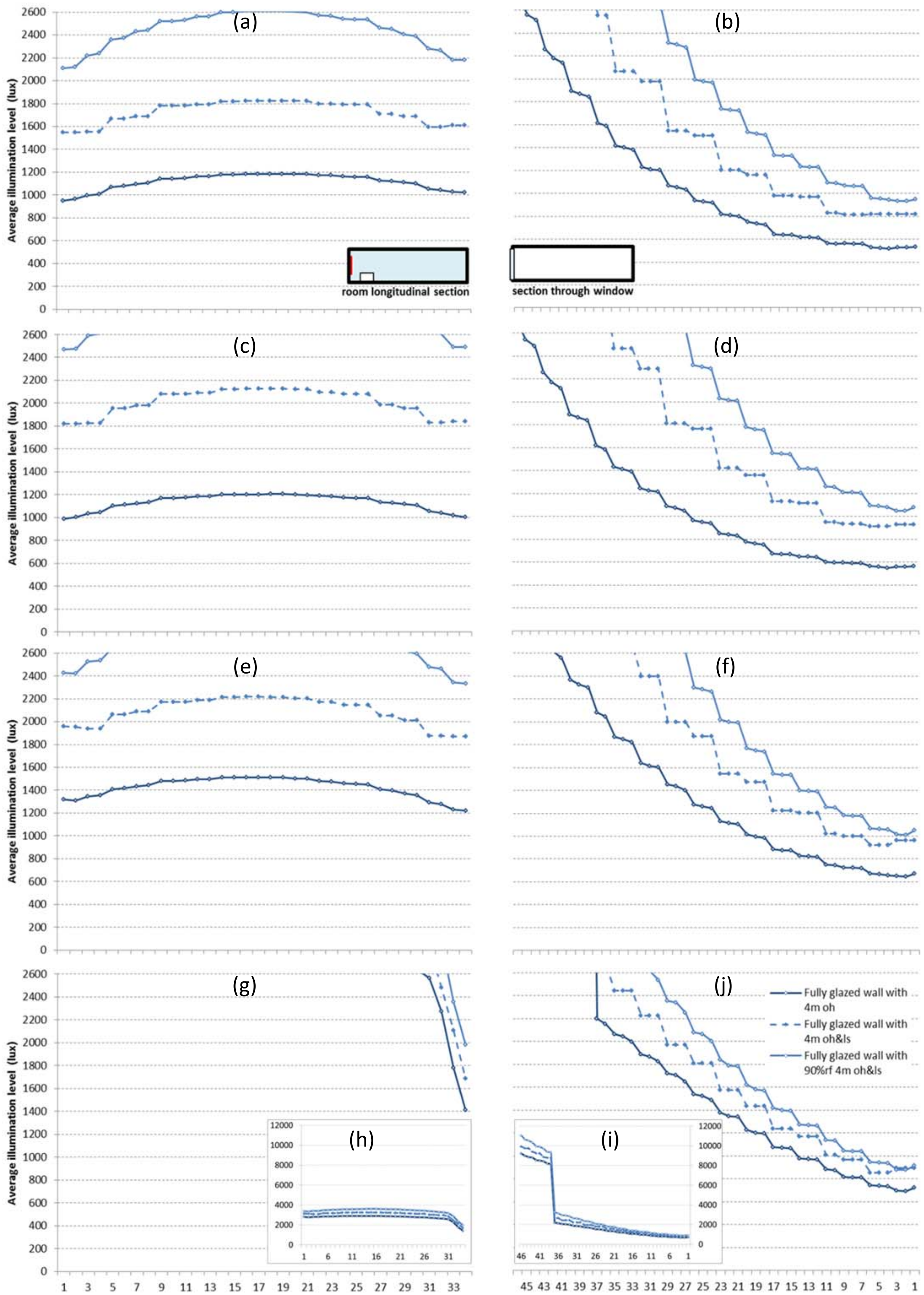


Fig.6. 48 Effect of light shelf reflectance on average illumination level under sunny clear sky on 22nd Jun. (a)-(b) 13:00, (c)-(d) 14:00, (e)-(f) 15:00 and (g)-(j) 16:00

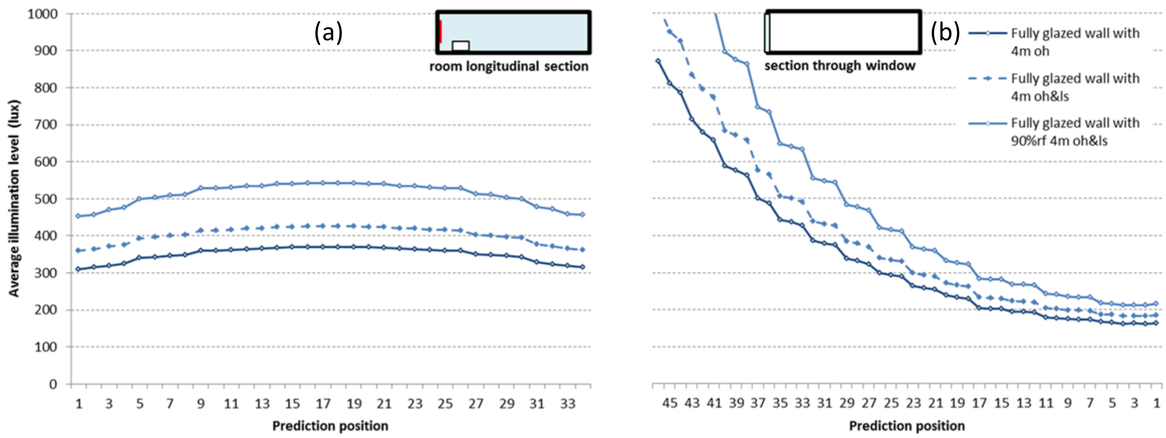


Fig.6. 49 Effect of light shelf reflectance on average illumination level under overcast sky (a) by room longitudinal section and (b) room cross section

Because the too limited benefit of light shelves which was already reported is unexpected, improvement of device reflectance was selected to be a further solution. The 70% of light shelf reflectance was replaced by the highest option which is 90% in order to examine the maximum effect of the device.

Unexpectedly, the improvement of the light shelf reflectance for the substantial large device generally provided slightly more daylight quantity. The maximum case was during 1PM – 2PM in December. The illuminance could be increased by about 50-200 lux in the furthest area from window in those limited periods. The increase in illuminances was much more than that from in front of the window to the mid of the room.

To sum up, limited advantage of reflecting elements and light shelf reflectance can imply that reflecting strategy may be able to improve daylight illuminance in general, but it cannot perfectly solve uniformity problems due to the reduction of increasing illuminance though the room section.

6.4 Effect of façade feature on natural ventilation

Apart from daylighting and thermal aspect which are research criteria, natural ventilation can be another concern for facade design. As a medium, building facade is the main heat protector and daylight deliverer. The previous results show necessity of facade elements which can also obstruct the window from the day light and view. Natural ventilation is another building design requirement that may not be allowed when using some facade feature. Although the university classrooms in Thailand as a tropical area are commonly operated with air conditioning system, natural ventilation can be essential in some cases that the

AC is not needed or unavailable. Consequently, effects of suggested facade on natural ventilation were investigated for either providing the suggestion supports or arguments.

Four type of facade in this study were selected for examining impact of each feature on natural ventilation using EnergyPlus function built in DesignBuilder software version 5 as the simulation tool. There were 'Base case', 'Fully glazed walls without overhang', 'Fully glazed walls with four metre deep overhang' and ' Fully glazed walls with one metre deep overhang and three light shelves'. For running the air flow rate analysis, the windows were set to be opened while all mechanical devices were excluded. The result shows in Figure 6.50. Expectedly, the fully glazed wall cases provide better result than the base case which is the existing classroom. The air flow rate of the case ‘Fully glazed walls with one metre deep overhang and three light shelves' is slightly higher than the rate of 'Fully glazed walls with four metre deep overhang'. When the two shading cases were compared to the non-shading one, it is considerably lower. Average air flow rate of the two shading cases are approximately from 25 to 45 ac/h higher than the base case for about 20-25 ac/h and lower than the non-shading case for 10-20 ac/h in approximate.

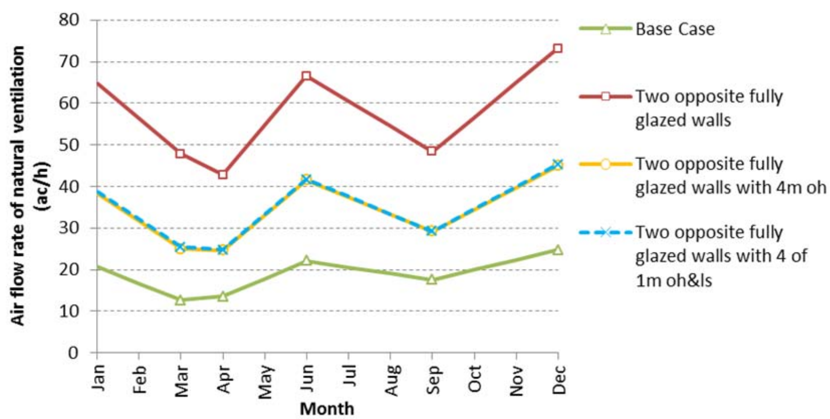


Fig.6. 50 Average air flow rate of natural ventilation for four shading types

According to BB101 (DFEE, 2014), the recommendation of minimum air flow rate for teaching spaces is 2.5 ac/h. Natural ventilation is recommended if possible. Higher air flow rate and mechanical supply are suggested for specialist teaching spaces, some service areas and some hygienic areas respectively. The rate is similar to the general space ventilation rate of 4 ac/h recommended by most professional institutions and authorities. The ventilation rate of classrooms is suggested in the range of 4-12 ac/h. In Thailand, there is specific regulation for neither natural ventilation nor educational buildings. Seven ac/h is the lower limit for air-conditioning offices and residential buildings in Thai Building Act 39. Comparing to recommendations and standards, air flow rate in all cases appear very high. However, the recommendations are for either lower limits or air conditioning systems. It is because air flow rates in closed AC rooms are commonly lower - in the range of 0.5-2 ac/h (Lstiburek, 2006).

Yao (2012) suggested variable air change rate as a useful solution in order to provide thermal comfort conditions for addressing different climates in summer and winter. Air change rates of 0.5 to 15 ac/h for closed and opened windows condition were found to be cost effective for reducing energy consumption. Rates over 15 ACH were suggested in the same study to provide more thermal comfort in summer. Recommendations of 2-15 ac/h by RIBA was mentioned by Passe and Battaglia (2015) for removing heat by cross ventilation. Similarly, 5-10 ac/h is a useful air change rate in summer according to Glicksman and Lin (2006). Temperature and RH inside the room with air change rates between 16-40 ac/h were found to be close to outdoor conditions. In this study, the fully glazed window without shading provided higher air change rates than the recommendations above, while air change rates of the cases with shading devices appeared to have similar conditions as the outdoor environment. The air change rates of base case façade are in the range of the recommendations. Since weather conditions in the winter daytime are generally in the comfort zone, the high air change rates during winter in all cases probably provide thermal comfort in the room. The study of Guo et.al (2008) confirms the occurrence of high air change rate in opened window classrooms. They also reported the advantage of high air change rate that can reduce particulate concentration. The result might show an advantage of the base case over other cases in terms of ventilation, but Yao's suggestion of variable air change rate reveals the importance of adjustable façade. For thermal comfort, air flow rates should be limited when applying AC for most of time, excluding in winter time. The result reveals that obstruction of the shading and reflecting elements can benefit natural ventilation in winter by reducing air flow rate which is excessive. Windows are required to be properly closed for using AC since the natural ventilation in summer daytime cannot benefit room thermal comfort.

6.5 Discussion

Comparing to the previous survey, occupants' satisfaction of the modified classroom appears not to be worse than the existing classroom. During the winter solstice the modified classroom was found generally to have sufficient illuminance without combining with artificial light, but it was doubtful in terms of visual comfort. The result also reveals that the occupants appear to be more sensitive to dim environments than bright environments as they noticed changes between dim and bright levels whereas they rarely noticed changes between bright and too bright. This is probably caused by the occupants' accustomed perception.

Boubekri and Boyer (1992), for example, found that a user now familiar with no-window space can overestimate daylighting conditions. In this study, in the opposite way, people in tropical climates who were familiar with overwhelming daylight may be able to accept much higher illuminance than set by a standard. In this case, the survey was obtained in a very open room with little shade during the average highest illuminance period of the year and most of the participants considered conditions as acceptable rather than perceiving glare.

Comparing the results of simulation, the prediction of the two opposite fully glazed walls without or with small shading device in the winter solstice were like the measurement in January 2015. They obviously provided substantially higher average illuminance and low higher illuminance ratio than standards (see Figure 5.12(c) and 5.14 for the prediction and Figure .6.4 and 6.5 for the measurement). However, predictions in Figure 5.11(c) showed that percentages of the room where illuminance did not meet standards were significantly low for both the winter and summer solstices. In addition, the luminance ratio (shown in Figure 6.6 and 6.7) and occupants' satisfaction (see Figure 6.10 and 6.12) imply that the occupants accepted the lighting environment in general. The results confirmed that the predictions appear to be sensible and the occupants can accept a larger range of daylight levels and variation than the standards indicate. Therefore, with more shading and less ceiling height, the suggested façade of this study should have better results in terms of visual comfort due to the fact that it will be less affected by direct sun than the modified classroom in the survey.

Apart from the brightness sensation, the practicability of the suggested solution for other classrooms was also examined. Different conditions consisting of window orientation, window area, room size, room proportion, corridor and façade feature were considered. The case of two opposite fully glazed walls with 30% of optimised shading depth appeared practical in most cases, with an additional limitation of not exceeding a 10-metre room width. For the cases of north orientation that required very limited shading, excessive high illuminance occurred in areas near the window, causing high brightness ratios. The generalization of 30% optimised shading depth can be in doubt. However, the acceptability of excessively high brightness ratio in the survey obtained in the modified classroom implies that the lower ratio occurred in the north orientation case can also be accepted.

When the opposite wall of window was not available, the most recommended strategy, reflecting devices, was combined with classroom façade. The effectiveness of the devices was generally found but in a different way. During the time with the direct effect of the low angle sun, such as in late afternoon and winter solstice afternoon, considerable improvement of illumination level was found in the furthest area of the room from the window. Without low angle sun, reflection from the devices benefits the area which not far from the window while in the furthest area it is insignificant increased illuminance.

The large shading device with window bottom light shelf was found to be the best solution in general, compared to the horizontal louver cases for the same vertical shadow angle. For the louvers, the smaller blades can provide better result. However, all devices can improve room illuminance in similar amounts. The large device appears to be impractical and not worth for the insignificant increased illumination levels. The louver can be used with similar result in terms of not only daylighting but also natural ventilation. When the windows were fully opened the existing façade appeared to be appropriate for ventilating the room, but it generally provided insufficient illuminance even when light shelves were included. Therefore, the fully glazed walls with shading and reflecting devices can be a good solution for both natural ventilation and daylighting. Theoretically, reflecting elements such as light shelves have been recommended for daylighting as one of the most effective solutions for sidelighting. Empirical results of this study agree with the suggestion but in a limited condition: with effect of low angle sun toward the window. According to the result, the devices appear to be needed in winter and in late afternoon when outdoor thermal is not too much warm. It is the time that thermal comfort can be achieved by applying full natural ventilation. It implies that an idea of adjustable façade should be considered mainly in winter time.

As the main component, the facade has been suggested to not to obstruct the view, daylight and natural ventilation while reflecting elements are also required. In order to optimise that need, this research investigated solutions for various conditions and found that none one of the façade features can perfectly solve daylighting and thermal issues due to variations of weather and sun geometry. Passive strategies, like the allowance of natural ventilation and additional illuminance from reflecting elements of the façade, should be introduced to the classroom in winter for further facade improvement. However, the daylighting environment was confirmed as suitable for general learning activities when the task was on the lecture desk and the general field of view rather than seeing the whiteboard and projector screen. Rather than façade design, the issues probably can be solved by a combination of other solutions such as applying less glossy tilted surfaces for the whiteboard, opaquer blinds and a higher quality of projector equipment.

Chapter 7

Conclusion and Recommendation

7.1 Conclusion

This study has investigated façade design solutions for classrooms in the tropical climate in Thailand using survey and simulation techniques as the main methods. The topic appears to have already been sorted out as many pieces of research and recommendation have been suggested as guidance for daylighting. However, some studies found that the suggested solutions should be different for each climate and building types and they were recommended in different ways. Conflicts and agreements of those findings were found in this research. The research findings, including limitations and suggestion for further work, are considered in this chapter.

1) Classroom façade design guideline

The aims of this study was to prioritize influential parameters and to suggest solutions of classroom façade design for daylighting in a tropical climate in order to recommend design guideline. The scope of study mainly is daylighting design, but it was necessary for a hot climate to investigate thermal aspect because daylighting can also allow heat resulting in discomfort and increasing cooling load.

a. Priority of parameters

Influential façade design parameters which were focused in this research consisted of window area, projecting depth of shading device and window orientation that related to influence of direct sun. There is an additional parameter which is daylighting control which has been found to have the most impact comparing to real façade parameters because daylighting will not be successful without the control system. In this case, the system includes manual operation of façade and lighting that involve occupants' behaviour. For the façade parameter itself, the most influential parameter is window area. Only this parameter can provide sufficient light level and reduce variations in daylight distribution. A shading device is the second priority as it can protect from heat and control excessive high illuminance, especially from direct sun. The parameter influences the impact of the other parameter, which is window orientation. Window orientation has the least impact because there will be no significant difference if proper shading depth is combined. However, orientation is the parameter that can hardly be changed after the design is fixed, therefore, it has to be considered in the preliminary stage of design.

b. Existing classroom façade improvement

With the existing façade, the daylight level was not enough, with visual discomfort in general even when the curtain was fully opened. The existing control system, which is curtain and artificial light, cannot properly control the daylight. There are three main problems for the three focused visual tasks: insufficient light level for lecture desk, veiling reflection for whiteboard and excessive high illuminance for using projector. For multi-function classrooms, the lighting environments provided must be different: bright for general use and dim for using projector. Daylighting conditions were proven as not practical for using a projector. Rather than applying daylight, control is needed. Focusing on general seeing and visual task on lecture desk, improvements of the existing façade can be suggested in two approaches.

At the very least, internal shading device and lighting layout should be changed as it is necessary for the existing facade. Lighting layout should be divided in to front area for the projector and parallel to the window above students' sitting area. The curtain should be more opaque and easier to operate like a lighting switch. In addition, the device should be fully opened as the default condition. Apart from all control switches having to be included in teacher's control panel, daylight level signals including instructions should be added in order to facilitate teachers to improve the lighting environment properly.

The depth of the existing overhang (2.1 metre depth) appears close to the recommendation of 30% of optimized shading device (1.8 metre depth) but it is noted that this depth of device can hardly control excessive high illuminance ratio. The existing window area was found to not be satisfactory, and uniformity difficulties were found. Therefore, refurbishment is required. With the existing window area, the addition of light shelves can slightly improve room illuminance in winter. When the cost of the device was considered compared with the benefit of reflection, the use of light shelves does not appear worthwhile. Suggested window area is a fully glazed wall with a four metre depth overhang - this would be much better in terms of daylighting if an additional window in the opposite side is included. According to the building structure, the recommendation is feasible to implement but with expensive construction costs.

c. Design guideline for new construction

For new constructions, two opposite fully glazed walls are recommended. No shading device is required if the window is orientated north and the south facing corridor, including its shading device, is four metre deep. However, whichever orientations can be assigned since 50% of optimized shading device is applied to the main window. Applying this recommendation, classrooms must be limited in room width to not be more than 10 metres. The addition of reflecting elements can improve daylighting illuminance but for a very limited time: in late afternoon and winter afternoons when low angle sun influences the façade. However, in the case that the large shading device is required, horizontal louvers applying the same vertical shadow angle can be more practical. Some elements of the devices may obstruct daylight and ventilation, but some elements also can improve indoor illuminance by reflecting the daylight into the room. Moreover, the large devices provide only slightly better results than the louvers. The use of louvers is not only more sensible but also more feasible to use for controlling the daylight. Although the more reflectance of the device provides the better result, high reflectance materials such as specular surface of aluminium have limitation. Like the effect of dust on window which was mentioned in Chapter 4, when dust covers surfaces materials will lose their reflective property. Regular maintenance is required for this strategy.

Artificial light may be less necessary in general, but it is still needed in case the illuminance from the sky is low, for example for overcast sky. Another alternative could be adjustable shading device form about 30% to 50% of optimized device between summer and winter. The operation can be successful when it is included into building operation schedule which should be run by Faculty staff.

Interior shading device is demanded for darkening the space when applying projector. Reflective or diffused device is less important than opaque device which is easy to be operated.

d. Additional recommendations

Suggestions which have been recommended are mainly about façade feature for daylighting in general use. However, there are some influential difficulties that cannot be solves by façade design and control system. The visual problem form veiling reflection on the whiteboard was found can cause by daylight and artificial light. Reduction of light intensity was found not successful because it results in directional reflection to students' eyes and only less amount of light from artificial can also cause problems. Simply, suggestion such as tilted the whiteboard was recommended.

Another problem related to artificial light is some amount of light was lost in ceiling cavity because the light was place above room structural beams. For more efficiency, the light should be placed at the lower level than the bottom of the beams.

2) Limitation

This study attempts to fill the gap of daylighting research especially for classrooms that daylighting level and occupants' satisfaction have been separately studied. Three methods were combined properly but some limitations were found and attempted to be fixed.

a. Difficulties of surveys

Although the building users and owners were willing to do surveys and partly understood about topic, when they were questioned some difficulties occurred in the real situation of three surveys. Availability of building data was one of the difficulties. Although having permission to use the data, actual cooling energy consumption or electrical bill, for example may be limited. Apart from this, the classrooms were irregularly occupied, with the whole building consisting of different types of classrooms, common areas, teachers' and staffs' offices. The problem was that no separate electricity meters for individual room or zone were installed. Moreover, the meter records were for the total electricity load of the case study building and other nearby buildings together. The actual cooling energy load of one lecture room then cannot be identified using meter readings or energy bills.

The surveys were planned and undertaken during June 2012, from December 2014 to January 2015 and from March to June 2017, which were different seasons and years. Inevitably, the weather and most of the participants were not the same. The results then were analysed under the different conditions. Although some issues were avoided in the surveys, there can be some errors when comparing satisfaction votes from different persons when there are time changes. Also, differences of five case studies means that they cannot be directly compared due to significantly different conditions, with the building and classrooms of the main case study slightly changed after two and three years – for example, different types of furniture in some rooms. Moreover, there were difficulties of the surveys for additional case studies. Firstly, at least three cases in different regions in tropical climate were required in order to represent the areas but in the real situation of field work more than the expected amount of the cases had to be surveyed in case of error. Secondly, in order to collect data, permission was required for all case studies. Some limitations, such as classroom schedule and availability, can cause missing data or delay. Lastly, time limit also depends on the weather which changes at all time. In this study, the most proper time which was selected is in equinox during March when most universities are in term time and most classrooms are generally used: not in examination period or too busy. The delay occurring in some cases resulting in late survey during June for the last case study. There is no occupied classroom available at the permitted time due to all courses already having finished.

Modifying a classroom is one of the most difficult issues in this research. Fortunately, there was a space with the same orientation that had two opposite fully glazed walls which was available to set up as a classroom, but for modifying the room in terms of shading device it was not feasible in the time limit; therefore, the shading device of the room and some different feature to the existing classroom was left. The survey then was done on the condition that the modified classroom can be worse than the suggested solutions.

b. Limited results of measurements

For measurement, fluctuation of daylight was always a problem, especially when the number of measuring equipment was limited. In this study, calibration of the different times and devices was done using regression analysis but there was a very small statistical sample size. This can cause some errors. Furthermore, the measurements were only obtained during the summer and winter solstice and so cannot represent year-round weather. However, this study attempted to apply the results of maximum and minimum cases that should be acceptable when considered with results of the other methods.

c. DesignBuilder limitations

DesignBuilder was selected to be the main device of simulation stage because the package is one of the programs that can analyse both daylighting and thermal aspects. The program was proved practical for daylighting analysis of tropical sky than Ecotect which is the other program that can predict all the studied aspects. However, daylighting analysis was a new function at the time the research commenced, and it has been developing during the simulation stage. A study of the program was included to be an important part of this research. The program may be good for simulation, but many limitations were found for daylighting analysis.

Firstly, the program cannot predict vertical luminance. It is only for horizontal illuminance on a working plane. An image of illuminance contours on layout of the room is the only result format that the program can provide, and it is difficult to compare. Secondly, it must be analysed for each hour for every case in terms of daylight. In addition, in order to make the results comparable, raw data have been drawn from the program, re-arranged from axis to matrix format and prepared for comparing. All tasks consumed much time while provided not many results. In this research, only working hour in specific dates were selected to represent difference of season in most part of the analysis. Thirdly, reflecting strategies such as a light shelf and reflected slats cannot be predicted by the program. Finally, incompatibility between EnergyPlus simulations and daylighting analysis was found. While daylighting control was applied, the simulation never detected an insufficiency of daylight. It was found that the simulation also can predict average illuminance for daylighting control of lighting system, but it overestimated the prediction of daylighting analysis function which was more sensible. Due to overestimation, lighting was not essential when applying daylighting control.

All limitations of the program result in difficulties as it is time consuming and cannot solve some of the research requirements. However, this research attempted to use DesignBuilder to its capacity for what was relevant to the research purposes.

7.2 Recommendation

Designing for daylighting has been studied in various approaches which had to specify condition for scoping the study. Although this study attempted to apply very simple features and techniques, the findings from only 4-5 classrooms represent specific conditions that probably cannot be applied more generally to every classroom of the same size. Due to the conditional result and limitations of this study, further recommendation and study are required for most benefit of classroom design.

1) Other application

According to the results in Chapter 6, the results of this study can be applied to improve existing classrooms and adapted to other similar cases in tropical climates. The cases should have room widths not more than 10 metres and connect to a single loaded corridor. The classroom with more room width or double loaded corridor should apply further complicate techniques such as light pipe or automatic reflectors. The size of the façade can be reduced if the device is adjustable. For new construction, room proportion and building orientation should be considered at the first stage. The orientations which provide less daylight illuminance such as east-west orientation should be either avoided in new design or applied with smaller room width.

However, the suggestion can be used in general for maximising the use of daylight in classrooms. The knowledge of the relationships between influential parameters such as shading depth, window area and orientation, can also apply in general and further intensive studies can generalise the results.

2) Future work

Two approaches can be further studied: the façade parameter and visual comfort investigation. There were influential parameters that were excluded from the scope of this study, such as glazing type and other types of shading device, including reflecting strategies. The study can continue from window area, shading depth and light shelves, which were suggested in this study for combining with other programs that can deal with the parameters. In terms of design, adjustability of the devices to suit the weather condition and building function can be interesting research areas. It is not only external devices but also interior shading device which daylighting control that should be examined. Manual control of daylighting in terms of lighting and interior façade must be included in the study.

In order to use prediction more efficiently for visual comfort, further study regarding the practicality of vertical luminance or glare index must be examined and compared to horizontal illuminance using similar process surveys, measurements and simulations. Specialist lighting programs such as RADIANCE and more complicated measurements have to be applied in future research. If relationships between the prediction and occupant satisfaction are intensively studied, predictions can indicate visual comfort more than is currently possible.

As a related field of classroom façade design, other comfort strategies such as passive and acoustic design should be considered. Façade design for daylighting in this research mainly focused on daylighting and thermal aspects in AC conditions. A study of passive cooling like natural ventilation is only in its preliminary stage and can basically show natural ventilation performance of suggested façade. In order to investigate the features that can enhance the ventilation, more time consuming and further complicated simulations are required. When natural light and ventilation are attempted to be applied to the classroom, the suitable façade features for those aspects theoretically possibly cause negative effects for acoustic. These research topics can be included in further study.

List of references

ACOSTA, I., MUNOZ, C., ESQUIVIAS, P., MORENO, D. & NAVARRO, J. 2015. Analysis of the accuracy of the sky component calculation in daylighting simulation programs, Solar Energy, 119, 54-67

AGHEMO, C., PELLEGRINO, A. & LOVERSO, V. R. M. 2008. The approach to daylighting by scale models and sun and sky simulators: A case study for different shading systems. Building and Environment, 43, 917-927.

AIZLEWOOD, M., LAFORGUE, P., CARROLL, W., BUTT, J., MITTANCHEY, R., & HITCHCOCK, R. 1998. Data Sets for the Validation of Daylighting Computer Programs. In: Proceedings of Daylighting 98, International Daylighting Conference 98. Ottawa, Ontario, Canada: 157-164.

ALRUBAIH, M., ZAIN, M., ALGHOUL, M., IBRAHIM, N., SHAMERI, M. & ELAYEB, O. 2013. Research and development on aspects of daylighting fundamentals. Renewable and Sustainable Energy Reviews, 21, 494-505.

ALTOMONTE, S. 2009. Daylight and the occupant: Visual and physio-psychological well-being in built environments. In: 26th Int. Conf. On Passive and Low Energy Architecture, 22-24 June 2009, Quebec City, Canada. 24.

AL-TAMIMI, N. A. & FADZIL, S. F. S. 2011. The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics. Procedia Engineering, 2 (2011), 273-282

ANDERSEN, R. V., TOFTUM, J. & OLESEN, B. W. 2009. Long Term Monitoring of Window Opening Behaviour. In: 26th Int. Conf. On Passive and Low Energy Architecture, 22-24 June 2009, Quebec City, Canada.

APPLE, C. L. S. 2008. Illuminance and Uniformity [Online]. Available: http://personal.cityu.edu.hk/~bsapplec/newpage317.htm [Accessed 30 July 2015].

ASHRAE 2010. Standard 55-2010, Thermal Environmental Conditions for Human Occupancy. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

BAKER, L. & BERNSTEIN, H. 2012. The impact of school buildings on student health and performance: A call for research. the Center for Green Schools at the U.S. Green Building Council.

BAKER, N. 2000. We are all outdoor animals. Architecture City Environment, In: 17th Int. Conf. On Passive and Low Energy Architecture, 2-5 July 2000, Cambridge, UK. 553-555.

BAKER, N. V. & STEEMERS, K. 2002. Daylight design of buildings, London : James & James.

BARRETT, P., DAVIES, F., ZHANG, Y. & BARRETT, L. 2015. The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis. Building and Environment, 89, 118-133.

BARRETT, P., ZHANG, Y., MOFFAT, J. & KOBBACY, K. 2013. A holistic, multi-level analysis identifying the impact of classroom design on pupils' learning. Building and Environment, 59, 678-689.

BELL, M. & KIM, J. 2009. Engineered Transparency : The Technical, Visual, and Spatial Effects of Glass, New York: Princeton Architectural Press.

BELLIA, L., CESARANO, A., IULIANO, G. F. & SPADA, G. 2008. Daylight glare: a review of discomfort indexes. Napoli: DETEC – Università degli Studi di Napoli Federico II

BINARTI, F. 2009. Energy-efficient window for classroom in warm tropical area. In: Eleventh International IBPSA Conference. Glasgow, Scotland.

BIRKELAND, J. 2002. Design for Sustainability : A Sourcebook of Integrated, Ecological Solutions. London: GBR, Earthscan.

BONEH, M. 1982. Environmental comfort in educational buildings: Influence of windows and other openings. Energy and Buildings, 4, 239-243.

BOUBEKRI, M. & BOYER, L. L. 1992. Effect of window size and sunlight presence on glare. Lighting research & technology, 24, 69-74.

BOYCE, P., HUNTER, C. & HOWLETT, O. 2003. The benefits of daylight through windows. New York: Rensselaer Polytechnic Institute.

BRE 2011. BREEAM 2011 for New Construction: Non-domestic buildings. Technical manual SD5073-2:0:2011. Watford: BRE Global Ltd.

BURIPRASERT, P. 2000. Side lighting types for daylighting utilization in office buildings (in Thai). Master of Architecture Thesis, Chulalongkorn University.

CANTIN, F. & DUBOIS, M. C. 2011. Daylighting metrics based on illuminance, distribution, glare and directivity. Lighting Research and Technology, 43, 291.

CAREW, P. & MPAULI, B. 2012. Daylight design: Simulations driven luminaire and controls selection. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru.

CATALINA, T. & IORDACHE, V. 2012. IEQ assessment on schools in the design stage. Building and Environment, 49, 129-140.

CEN 2005. EN 14501 Blinds and Shutters - Thermal and Visual Comfort - Performance Characteristics and Classification. European Committee for Standardization.

CHAIWIWATWORAKUL, P. 2011. Daylighting in the tropics: Daylight availability, sky Luminance distribition, daylight application with automated blind Saarbrucken, LAP LAMBERT Academic Publishing GmbH & Co. KG.

CHAIWIWATWORAKUL, P., CHIRARATTANANON, S. & RAKKWAMSUK, P. 2009. Application of automated blind for daylighting in tropical region. Energy Conversion and Management, 50, 2927-2943.

CHAUVEL, P., COLLINS, J. B., DOGNIAUX, R. & LONGMORE, J. 1982. Glare from windows: current views of the problem. Lighting Research & Technology, 14, 31.

CHIRARATTANANON, S., CHAIWIWATWORAKUL, P. & PATTANASETHANON, S. 2002. Daylight availability and models for global and diffuse horizontal illuminance and irradiance for Bangkok. Renewable Energy, 26, 69-89.

CHIRARATTANANON, S., CHEDSIRI, S. & RENSHEN, L. 2000. Daylighting through light pipes in the tropics. Solar Energy, 69, 331-341.

CHIRARATTANANON, S., NOORITANON, J. & BALAKA, R. 1996. Daylighting for energy conservation in the tropics: The lumen method and the OTTV. Energy, 21, 505-510.

CHOU, D. 1998. A simplified estimation method for power consumption of buildings lighting designs. Journal of Architecture, 22, 23-24.

CHOU, P., CHIANG, C. & CHANG, K. 2004. Predicted simulation on the lighting energy saving in a classroom using the sun shading as the daylight-introducing device. In: 21th Int. Conf. On Passive and Low Energy Architecture, 19 - 22. September 2004, Eindhoven, The Netherlands. 1-4.

CHOW, S. K. H., LI, D. H. W., LEE, E. W. M. & LAM, J. C. 2013. Analysis and prediction of daylighting and energy performance in atrium spaces using daylight-linked lighting controls. Applied Energy, 112, 1016-1024.

CHPS 2006. Best Practices Manual Volume III: criteria. California: Collaborative For High Performance Schools

CHRISTAKOU, D. E. & AMORIM, C. N. D. 2005. Daylighting simulation: comparison of softwares for architect s utilization. In: Ninth International IBPSA Conference, Montreal, Canada, August 15-18, 2005. 183-186

CHUNGLOO, S., LIMMEECHOKCHAI, B. & CHUNGPAIBULPATANA, S. 2001a. Energy Efficient Design of Side-Window for Day lighting Application in Thailand. In: Seventh International IBPSA Conference, Rio de Janeiro, Brazil.

CHUNGLOO, S., LIMMEECHOKCHAI, B. & CHUNGPAIBULPATANA, S. 2001b. Energy Efficient Fenestration for Daylighting Apptication in Thailand. Thammasat Int. J. Sc. Tech, 6.

CIBSC 1994. CIBSE Code for interior lighting. London: The Chartered Institute of Building Services Engineers.

CIBSC 2011. CIBSE Lighting Guide LG5: Lighting for Educational. London: The Chartered Institute of Building Services Engineers.

CSBR 2011. The Efficient Windows Collaborative Tools for Schools. Washington D.C.: Efficient Windows Collaborative.

DA SILVA, P. C., LEAL, V. & ANDERSEN, M. 2012. Influence of shading control patterns on the energy assessment of office spaces. Energy and Buildings, 50, 35-48.

DAVID, M., DONN, M., GARDE, F. & LENOIR, A. 2011. Assessment of the thermal and visual efficiency of solar shades. Building and Environment, 46, 1489-1496.

DE GIULI, V., ZECCHIN, R., SALMASO, L., CORAIN, L. & DE CARLI, M. 2013. Measured and perceived indoor environmental quality: Padua Hospital case study. Building and Environment, 59, 211-226.

DEMOS, G., DAVIS, S. & ZUWAYLIF, F. 1967. Controlled physical environments. *Building Research,* 4, 60-62.

DENAN, Z. 2004. Assessment of window and lighting design in office buildings under daylight condition of a hot-humid climate, Malaysia. Doctor of Philosophy, University of Wales.

DFEE 1999. Building Bulletin 90: Lighting Design for Schools. London: Department for Education and Environment.

DFEE 2014. Building Bulletin 101: Ventilation for School Buildings. London: Department for Education Funding Agency.

DUBOIS, M.-C. 2003. Shading devices and daylight quality: an evaluation based on simple performance indicators. Lighting Research & Technology, 35, 61-76.

EDMONDS, I. R. & GREENUP, P. J. 2002. Daylighting in the tropics. Solar Energy, 73, 111-121.

ELKADI, H. 2006. Cultures of Glass Architecture, Abingdon, Oxon, GBR, Ashgate Publishing Group.

FAKRA, A. H., BOYER, H. & MAAMARI, F. 2008. Experimental validation for software DIALUX: application in CIE test Cases for building daylighting simulation. In: International Conference on Building Energy and Environment (COBEE 2008), Jul 2008, Dalian, China. <hal01198696>

FAKRA, A. H., BOYER, H., MIRANVILLE, F. & BIGOT, D. 2011. A simple evaluation of global and diffuse luminous efficacy for all sky conditions in tropical and humid climate. Renewable Energy, 36, 298-306

FAKRA, A. H., MIRANVILLE, F., BOYER, H. & GUICHARD, S. 2011. Development of a new model to predict indoor daylighting: Integration in CODYRUN software and validation. Energy Conversion and Management, 52, 2724–2734

FANGER, P. O. 1970. Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

FFC 2001. Learning from Our Buildings : A State-of-the-Practice Summary of Post-Occupancy Evaluation. Washington, DC: National Academies Press.

FFC 2005. Implementing Health-Protective Features and Practices in Buildings: Workshop Proceedings-Federal Facilities Council Technical Report Number 148, National Academies Press.

FISEKIS, K., DAVIES, M., KOLOKOTRONI, M. & LANGFORD, P. 2003. Prediction of discomfort glare from windows. Lighting Research and Technology, 35, 360-369.

FISHER, A. V., GODWIN, K. E. & SELTMAN, H. 2014. Visual Environment, Attention Allocation, and Learning in Young Children When Too Much of a Good Thing May Be Bad. Psychological Science, 25, 1362-1370.

FREEWAN, A. A. , SHAO, L., & RIFFAT, S. 2008. Optimizing performance of the lightshelf by modifying ceiling geometry in highly luminous climates. Solar Energy, 82, 343–353

FREEWAN, A. A. Y. 2014. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. Solar Energy, 102, 14-30.

GALASIU, A.D. & ATIF, M.R. 1998. Application of daylighting computer modeling in real case studies: comparison between measured and simulated daylight availability and lighting consumption. A report of IEA SHC Task 21 / IEA ECBCS Annex 29 Daylight in Buildings November 1998. National Research Council Canada, Institute for Research in Construction, Indoor Environment Research Program

GALASIU, A. D. & ATIF, M. R. 2002.Applicability of daylighting computer modeling in real case studies: comparison between measured and simulated daylight availability and lighting consumption. Building and Environment, 37, 363–377

GAGNEL, J. M. L. & ANDERSEN, M. 2010. Multi-objective facade optimization for daylighting design using a genetic algorithm In: 4th National Conference of IBPSA-USA SimBuild 2010, 11-13 August 2010, New York, USA.

GHISI, E. & TINKER, J. A. 2005. An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings. Building and Environment, 40, 51-61.

GUPTA, R. & CHANDIWALA, S. 2010. Understanding occupants: feedback techniques for large-scale low-carbon domestic refurbishments. Building Research & Information, 38, 530-548.

GUTH, S. K. 1966. Computing visual comfort ratings for a specific interior lighting installation. Illuminating Engineering, 61, 634.

HALLIDAY, S. 2008. Sustainable Construction, Jordan Hill, GBR, Spon Press.

HARRIS, C. M. 2005. Dictionary of architecture and construction, McGraw-Hill Professional.

HATHAWAY, W. E. 1995. Effects of school lighting on physical development and school performance. Journal of Educational Research, 88, 228.

HATHAWAY, W. E., HARGREAVES, J. A., THOMPSON, G. W. & NOVITSKY, D. 1992. A Study into the Effects of Light on Children of Elementary School Age: A Case of Daylight Robbery. Policy and Planning, Branch Planning and Information Services Division, Alberta Education.

HAUSLADEN, G. & LIEDL, P. 2012. Building to Suit the Climate : A Handbook, Basel, CHE, Birkhaeuser.

HESCHONG, L., WRIGHT, R. L. & OKURA, S. 2002. Daylighting Impacts on Human Performance in School. Journal of the Illuminating Engineering Society, 31, 101.

HIGUCHI, S., HAYAMA, H. & ENAI, M. 2009. Influence of eave length and diffusion on window in the school classroom onto an annual heat load and a daylight illumination. AIJ Journal of Technology and Design, 15, 797-802.

HO, M.-C., CHIANG, C.-M., CHOU, P.-C., CHANG, K.-F. & LEE, C.-Y. 2008. Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms. Energy and Buildings, 40, 1844-1855.

HUNT, D. R. G. 1979. The use of artificial lighting in relation to daylight levels and occupancy. Building and Environment, 14, 21-33.

IES 1989. IES Recommended Practice for the Lumen Method of Daylight Calculations. RP-23-1989. New York, U.S.A.: Illuminating Engineering Society.

IESNA 2000. Lighting Handbook: Reference and application volume. New York: Illuminating Engineering Society of North America.

IHM, P., NEMRI, A. & KRARTI, M. 2009. Estimation of lighting energy savings from daylighting. Building and Environment, 44, 509-514.

INANICI, M. N. & DEMIRBILEK, F. N. 2000. Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. Building and Environment, 35, 41-52.

INKAROJRIT, V. 2005. Balancing comfort: occupants' control of window blinds in private offices. Doctor of Philosophy, University of California.

INNOVATIVEDESIGN 2004. Guide for daylighting schools. North Carolina, USA.

INTARAKULCHAI, B. 2013. Enhance daylighting quality of architecture studio in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University (in Thai). JARS: Journal of Architectural/Planning Research and Studies, 10, 45-65.

ISI 1975. Indian Standard Guide for 'daylighting of buildings'. New Delhi, India: Indian Standards Institution.

JAKICA, N. 2018. State-of-the-art review of solar design tools and methods for assessing daylighting and solar potential for building-integrated photovoltaics. Renewable and Sustainable Energy Reviews, 81, 1296–1328

JALOXA. 2014. Sunpath Diagram of 16 North [Online]. Available: http://www.jaloxa.eu/resources/daylighting/sunpath.shtml [Accessed 4 July 2015].

KAKHAM, P., RAKKWAMSUK, P., CHIRARATTANANON S. & CHAIWIWATWORAKUL, P. 2010. A study of appropriate blinds for maximum benefit of daylighting (in Thai). In: The 6th Conference on Energy Network of Thailand, 5-7 May 2010 Bangkok, Thailand

KHEDARI, J., YAMTRAIPAT, N., PRATINTONG, N. & HIRUNLABH, J. 2000. Thailand ventilation comfort chart. Energy and Buildings, 32, 245-249.

KIM, J.-H., MIN, Y.-K. & KIM, B. 2013. Is the PMV index an indicator of human thermal comfort sensation. International Journal of Smart Home, 7, 27-34.

KIM, J. T. & KIM, G. 2010. Advanced external shading device to maximize visual and view performance. Indoor and Built Environment, 19, 65-72.

KIRIMTAT, A., KOYUNBABA, B. K., CHATZIKONSTANTINOU, I. & SARIYILDIZ, S. 2016. Review of simulation modelling for shading devices in buildings. Renewable and Sustainable Energy Reviews, 53, 23–49

KJELL, A. 2014. Design energy simulation for architects: guide to 3D graphics, London, Taylor & Francis Ltd.

KNAACK, U. & KLEIN, T. 2009. Research in Architectural Engineering : Future Envelope 2 : Architecture - Climate - Skin, Amsterdam, NLD, IOS Press.

KONG, X., LU, S., GAO, P., ZHU, N., WU, W. & CAO, X. 2012. Research on the energy performance and indoor environment quality of typical public buildings in the tropical areas of China. Energy and Buildings, 48, 155-167.

KRU, E.L. & LUCIO, A. 2008 . Daylighting analysis in a public school in Curitiba, Brazil . Renewable Energy, 33(7), 1695–1702

KVDP. 2013. World map indicating tropics and subtropics. World: Wikimedia Commons. [Online]. Available: https://commons.wikimedia.org/wiki/File:World_map_indicating_tropics_and_subtropics.png [Accessed 4 July 2015].

LAM, K. P., MAHDAVI, A., ULLAH, M. B., NG, E. & PAL V. 1999. Evaluation of six sky luminance prediction models using measured data from Singapore. Lighting Research Technology, 31(1), 13-17

LARSON, C. T. 1965. *The effect of windowless classrooms on elementary school children*, Architectural Research Laboratory, Department of Architecture, University of Michigan, USA.

LE HONG, M. & RODRIQUES, L. 2013. Visual and Thermal Performance in Façade Design. In: 29th Int. Conf. On Passive and Low Energy Architecture 10-12 September 2013, Munich, Germany.

LEE, H., KIM, K., SEO, J. & KIM, Y. 2017. Effectiveness of a perforated light shelf for energy saving. Energy and Buildings, 144, 144–151

LEE, K. S., KI JUN HAN, K. J. & LEE, J. W. 2016. Feasibility study on parametric optimization of daylighting in building shading design. Sustainability 2016, 8, 1-16

LEE, M. C., MUI, K. W., WONG, L. T., CHAN, W. Y., LEE, E. W. M. & CHEUNG, C. T. 2012. Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms. Building and Environment, 49, 238-244.

LEROUX, M. & GOSSELIN, L. 2012. Optimisation of Glazing Area Façade and Glass Type of a Low-Energy Office Building with CLT and Concrete Floor Slabs. In: 28th Int. Conf. On Passive and Low Energy Architecture 7-9 November 2012, Lima, Perú

LEUNG, M. Y. & FUNG, I. 2005. Enhancement of classroom facilities of primary schools and its impact on learning behaviors of students. Facilities, 23, 585-594.

LI, D. H. & LAM, J. C. 2003. An investigation of daylighting performance and energy saving in a daylit corridor. Energy and Buildings, 35, 365-373.

LI, D. H. W. & LAM J. C. 2004. Predicting daylight illuminance by computer simulation techniques. Lighting

Research Technology, 36(2), 113-129

LIBBEY-OWENS-FORD COMPANY. 1976. How to predict interior daylight illumination : Conserve energy and increase visual performance by effective daylight design, Ohio, Libbey-owens-ford company

LIM, Y., AHMAD, M. H. & OSSEN, D. R. 2013. Internal shading for efficient tropical daylighting in Malaysian contemporary high-rise open plan office. Indoor Built Environ 2013, 22(6), 932–951

LIM, Y., & HENG, C. Y. S. 2016. Dynamic internal light shelf for tropical daylighting in high-rise office buildings. Building and Environment, 106, 155-166

LIM, Y. W. & AHMAD, M. H. 2015. The effects of direct sunlight on light shelf performance under tropical sky. Indoor and Built Environment, 24(6), 788–802

LIM, Y. W., KANDAR, M. Z., AHMAD, M. H., OSSEN, D. R. & ABDULLAH, A. M. 2012. Building facade design for daylighting quality in typical government office building. Building and Environment, 57, 194-204.

LINHART, F., WITTKOPF, S. K. & SCARTEZZINI, J. L. 2010. Performance of Anidolic Daylighting Systems in tropical climates - Parametric studies for identification of main influencing factors. Solar Energy, 84, 1085-1094.

LOE, D., WATSON, N., ROWLANDS, E., MANSFIELD, K., VENNING, B., BAKER, J., DEPARTMENT FOR, E., EMPLOYMENT, L. A. & BUILDING, B. 1999. Lighting Design for Schools. Building Bulletin 90.

LOUTZENHISER, P. G., MAXWELL, G. M. & MANZ, H. 2007.An empirical validation of the daylighting algorithms and associated interactions in building energy simulation programs using various shading devices and windows. Energy, 32, 1855–1870

LOVE, J. A. 1990. The vertical-to-horizontal illuminance ratio: Development of a new indicator of daylighting performance. Michigan Univ., Ann Arbor, MI (United States).

MAAMARI, F. & FONTOYNONT, M., 2003. Analytical tests for investigating the accuracy of lighting programs. Lighting Research Technology, 35 (3), 225–242.

MAAMARI, F., FONTOYNONT, M. & ADRA, N. 2006.Application of the CIE test cases to assess the accuracy of lighting computer programs.Energy and Buildings, 38, 869–877

MAITREYA, V. K. 1979. Integrated design for school buildings. Building and Environment, 14, 119-124.

MANGKUTO, R. A. 2016. Validation of DIALux 4.12 and DIALux evo 4.1 against the Analytical Test Cases of CIE 171:2006, LEUKOS, 12(3), 139-150

MARDALJEVIC, J. 1995. Validation of a lighting simulation program under real sky condition. Lighting Research Technology, 27(4), 181-188

MARDALJEVIC, J. 2001. The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques. Lighting Research Technology, 33(2), 117-136

MARDALJEVIC, J. 2004. Verification of program accuracy for illuminance modelling: assumptions, methodology and an examination of conflicting findings. Lighting Research Technology, 36 (3), 217-242

MARKUS, T. A. 1967. The function of windows—a reappraisal. Building Science, 2, 97-121.

MARKUS, T. A. & MORRIS, E. N. 1980. Buildings, climate, and energy, London, Pitman Pub.

MARTINEZ, A., NOBLE, D., SCHILER, M. & PATTERSON, M. 2012. Facade Retrofit: Strategies for energy reduction in an office building in a mild climate. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru.

MISHRA, A. K. & RAMGOPAL, M. 2013. Field studies on human thermal comfort - An overview. Building and Environment, 64, 94-106.

MOAZZENI, M. H. AND GHIABAKLOU, Z. 2016. Investigating the Influence of Light Shelf Geometry Parameters on Daylight Performance and Visual Comfort, a Case Study of Educational Space in Tehran, Iran. Buildings 2016, 6(26), 1-16

MONTAZAMI, A., GATERELL, M. & NICOL, F. 2015. A comprehensive review of environmental design in UK schools: History, conflicts and solutions. Renewable and Sustainable Energy Reviews, 46, 249-264.

MONTENEGRO, E., POTVIN, A. & DEMERS, C. 2012. Impact of School Building Typologies on Visual, Thermal and Energy Performances. In: Proc. 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru. 1-8.30.

MOSKOW, K. 2008. Sustainable Facilities : Green Design, Construction, and Operations, New York, NY, USA, McGraw-Hill.

MUHAISEN, A. S. & DABBOOR, H. R. 2015. Studying the Impact of Orientation, Size, and Glass Material of Windows on Heating and Cooling Energy Demand of the Gaza Strip Buildings. Journal of Architecture and Planning, 27, 1-15.

NABIL, A. & MARDALJEVIC, J. 2006. Useful daylight illuminances: A replacement for daylight factors. Energy and Buildings, 38, 905-913.

NAZZAL, A. A. 2000. A New Daylight Glare Evaluation Method. Journal of Light & Visual Environment, 24, 19-27.

NAZZAL, A. A. 2001. A new daylight glare evaluation method: Introduction of the monitoring protocol and calculation method. Energy and Buildings, 33, 257-265.

NAZZAL, A. A. 2005. A new evaluation method for daylight discomfort glare. International Journal of Industrial Ergonomics, 35, 295-306.

NG, E. Y., POH, L.K., WEI, W. & NAGAKURA, T. 2001. Advanced lighting simulation in architectural design in the tropics. Automation in Construction, 10, 365–379

NICHOLLS, R. 2002. Low energy design, Oldham, Interface Publishing.

OCHOA, C.E., ARIES, M.B.C. & HENSEN, J.L.M., 2012. State of the art in lighting simulation for building science: a literature review. Journal of Building Performance Simulation, 5, 209–233.

OSTERHAUS, W. K. 2005. Discomfort glare assessment and prevention for daylight applications in office environments. Solar Energy, 79, 140-158.

PALMERO-MARRERO, A. I. & OLIVEIRA, A. C. 2010. Effect of louver shading devices on building energy requirements. Applied Energy, 87, 2040-2049.

PATTANASETHANON, S., LERTSATITTHANAKORN, C., ATTHAJARIYAKUL, S. & SOPONRONNARIT, S. 2007. All sky modeling daylight availability and illuminance/irradiance on horizontal plane for Mahasarakham, Thailand. Energy Conversion and Management, 48, 1601-1614.

PEREZ, M., OTEIZA, P. & NEILA, J. 2012. Fragmented Light Shelf: Sun protection system and daylighting optimization. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru.

PEREZ, Y. V. & CAPELUTO, I. G. 2009. Climatic considerations in school building design in the hot-humid climate for reducing energy consumption. Applied Energy, 86, 340-348.

PIDERIT, B. & BODAR, M. 2012. Design strategies applied to classroom's daylight design: Optimization of classrooms design. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru

PLATZER, W. 2003. Architectural and Technical Guidelines–Handbook for the Use of Switchable Facades Technology, Freiburg, Fraunhofer Institute for Solar Energy Systems.

RAHIM, R., BAHARUDDIN & MULYADI, R. 2004. Classification of daylight and radiation data into three sky conditions by cloud ratio and sunshine duration. Energy and Buildings, 36, 660-666.

RAMASOOT, T. & FOTIOS, S. 2009. The model of DSE user acceptability and performance: Derivation of new lighting recommendation for the classroom of the future. In: 26th Conference on Passive and Low Energy Architecture, 22-24 June 2009 Quebec City, Canada. 269-274.

RAMOS, G. & GHISI, E. 2010. Analysis of daylight calculated using the EnergyPlus programme. Renewable and Sustainable Energy Reviews, 14, 1948–1958

REA, M. S. 1984. Window blind occlusion: a pilot study. Building and Environment, 19, 133-137.

REA, M. S. 2000. The IESNA Lighting Handbook: Reference and Application. Lighting Handbook. New York: Illuminating Engineering Society of North America

REINHART, C., BOURGEOIS, D., DUBROUS, F., LAOUADI, A., LOPEZ, P. & STELESCU, O. 2007. Daylight1-2-3: a-state-of-the-art daylighting/energy analysis software for initial design investigations. Proceedings: Building Simulation 2007, 1669-1676

REINHART, C. F.& ANDERSEN, M. 2006. Development and validation of a Radiance model for a translucent panel. Energy and Buildings, 38, 890-904

REINHART, C. F. & VOSS, K. 2003. Monitoring manual control of electric lighting and blinds. Lighting Research and Technology, 35, 243-258.

REINHART, C. F. & WALKENHORST, O. 2001. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings, 33, 683-697

ROBSON, E. R. 1874. School architecture : being practical remarks on the planning, designing, building, and furnishing of school-houses, London, John Murray.

RTG 1994. Ministerial Regulations No.39 B.E.2537(1994) by Building Control Act B.E.2522 (1979) *In:* GOVERNMENT, R. T. (ed.). Bangkok: Royal Thai Government.

RUPP, R. F. & GHISI, E. 2012. Sizing Window Areas for Daylighting and Hybrid Ventilation in Commercial Buildings. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru.

SAIHONG, N. & SRISUTAPAN, A. 2007. Guidelines for lighting design in multimedia classroom (in Thai). Journal of Architectural/Planning Research and Studies, 5, 67-81.

SAMANI, S. A. & SAMANI, S. A. 2012. The impact of indoor lighting on students' learning performance in learning environments: a knowledge internalization perspective. Int J Business Soc Sci, 3, P127-P136.

SARAIJI, R., SAFADI, M. Y. A., GHAITHI, N. A. & MISTRICK, R. G., 2015. A comparison of scale-model photometry and computer simulation in day-lit spaces using a normalized daylight performance index. Energy and Buildings, 89, 76-86

SARAWGI, T. 2004. Determining the suitability of computer_aided daylight simulation method in the design process. International Journal of Architectural, 2(2), 155-175

SARIDAR, S. M. 2004. The impact of facade design on daylighting performance in office buildings: The case of Beirut, Lebanon. Doctor of Philosophy, University of Newcastle upon Tyne.

SHARMA, M. & ALI, S. 1978. Evaluation of thermal stress-tropical summer index. Building Digest, 127.

SILVESTRE, C., ANDRE, P. & MICHEL, T. 2009. Air temperature and CO2 variations in a naturally ventilated classroom under a Nordic climate. In: 26th Conference on Passive and Low Energy Architecture, 22-24 June 2009 Quebec City, Canada.

SLEEGERS, P., MOOLENAAR, N., GALETZKA, M., PRUYN, A., SARROUKH, B. & VAN DER ZANDE, B. 2012. Lighting affects students' concentration positively: findings from three Dutch studies. Lighting Research and Technology, 1477153512446099.

SLL 2003. *Code for lighting,* Oxford Society of Light and Lighting.

SLL 2014. Lighting for the built environment. LG10: Daylighting-a guilde for designers. Norwich: The Society of Light and Lighting.

SMITH, P. 2005. Architecture in a Climate of Change, Jordan Hill, GBR, Architectural Press.

STEEMERS, K. 1994. Daylighting design: Enhancing energy efficiency and visual quality. Renewable Energy, 5, 950-958.

STEIN, B., REYNOLDS, J. S. & MCGUINNESS, W. J. 1992. Mechanical and electrical equipment for buildings, New York, J. Wiley & Sons.

STEWART, D. M. 1981. Attitudes of school children to daylight and fenestration. Building and Environment, 16, 267-277.

STRAKA, V. & ALEKSIC, M. 2009. Post-occupancy evaluation: Three schools from Greater Toronto. In: 26th Conference on Passive and Low Energy Architecture, 22-24 June 2009 Quebec City, Canada.

SUN, C., GILES, H. & LIAN, Z. 2016. Parametric regression model for lighting calibration. Indoor and Built Environment, 25(2), 407-423

SUPANSOMBOON, S. 1998. Application of shading device . [data file], CU, Bangkok. Unpublished dataset, cited with permission.

SUPANSOMBOON, S. 2002. An investigation of factor effecting natural sidelighting illumination for general building (in Thai). Master of Architecture Chulalongkorn University.

SUPANSOMBOON, S. & SHARPLES, S. 2013. Availability and use of natural light in multi-function classrooms in Thailand. In: Buid SB13 Dubai conference, 8-10 December 2013, Dubai, UAE. 134.1-134.9.

TANGPOONSUPSIRI, T. 2001. An approach to improve visual comfort in classroom in rural areas (in Thai). Master of Architecture Thesis, Chulalongkorn University.

TANNER, C. K. 2000. The influence of school architecture on academic achievement. Journal of Educational Administration, 38, 309.

TANNER, C. K. 2009. Effects of school design on student outcomes. Journal of Educational Administration, 47, 381-399.

TENNESSEN, C. M. & CIMPRICH, B. 1995. Views to nature: Effects on attention. Journal of Environmental Psychology, 15, 77-85.

TGBI 2013. Thai's Rating of Energy and Environmental Sustainability for Preparation of New Building Construction & Major Renovation: TREES-PRE NC Version1.1 (in Thai). Bangkok: Thailand Green Building Institute.

THEODORSON, J. 2009. Daylit Classrooms at 47N, 117W: Insights from occupation. In: 26th Int. Conf. On Passive and Low Energy Architecture, 22-24 June 2009, Quebec City, Canada.

THIRAKOMEN, K. 2001. Humidity Control for Tropical Climate: . ASHRAE Thailand Chapter 2001-2002. ASHRAE Thailand.

TIAN, C., CHEN, T. & CHUNG, T. 2001. Experimental and simulating examination of computer tools, Radlink and DOE2, for daylighting and energy simulation with venetian blinds. Applied Energy, 124, 130–139

TIEA 2003. TIEA-GD003 Thailand indoor illuminance recommendations (in Thai). Bangkok, Thailand: Illuminating Engineering Association of Thailand.

TILDER, L. & BLOSTEIN, B. 2009. Design Ecologies : Sustainable Potentials in Architecture, New York, NY, USA, Princeton Architectural Press.

TMD. 2012a. 30 year average (1961-1990) [Online]. Bangkok: Thai Meteorology Department. Available: www.tmb.go.th [Accessed 23 November 2012].

TMD. 2012b. The Climate of Thailand [Online]. Bangkok: Thailand Meteorological Department. Available: http://www.tmd.go.th/en/archive/thailand_climate.pdf [Accessed 8 August 2015].

TMD. 2012c. Gathering Data by time slot [Online]. Bangkok: Thai Meteorology Department. Available: http://www.aws-observation.tmd.go.th/web/reports/ [Accessed 23 November 2012].

TORRES, S. & SAKAMOTO, Y. 2007. Facade design optimisation for daylight with a simple genetic algorithm. In: Proceedings of Building Simulation, 2007.

TREGENZA, P. 2003. Tropical daylighting. Lighting Research and Technology, 35, 1-2.

UBBELOHDE, M. S. & HUMANN, C. 1998. Comparative evaluation of four daylighting software programs. University of California, Berkeley, CA

ULRICH, R. 1984. View through a window may influence recovery from surgery. Science, 224, 224-225.

USGBC 2009. LEED 2009 for new construction and major renovations rating system: with alternative compliance paths for projects outside the U.S. Washington, DC: U.S. Green Building Council.

VAN DEN WYMELENBERG, K. 2012. Patterns of occupant interaction with window blinds: A literature review. Energy and Buildings, 51, 165-176.

VARENDORFF, A. & GARCIA HANSEN, V. 2012. Building envelope: performance optimisation processes for a daylight responsive architecture. In: 28th Int. Conf. On Passive and Low Energy Architecture, 7-9 November 2012, Lima, Peru. Passive & Low Energy Architecture, 1-6.

VISITSAK, S. 2007. An evaluation of the bioclimatic chart for choosing design strategies for a thermostatically-controlled residence in selected climates. Doctor of Philosophy, Texas A&M University.

WANG, H. & ZHAI, Z. 2016. Advances in building simulation and computational techniques: A review between 1987 and 2014. Energy and Buildings, 128, 319-335

WIENOLD, J. 2009. Dynamic daylight glare evaluation. In: Proceedings of Building Simulation, 2009. 27-30.

WIENOLD, J. & CHRISTOFFERSEN, J. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38, 743-757.

WINTERBOTTOM, M. & WILKINS, A. 2009. Lighting and discomfort in the classroom. Journal of Environmental Psychology, 29, 63-75.

WITTKOPF, S. K. & SOON, L. K. 2007. Analysing sky luminance scans and predicting frequent sky patterns in Singapore. Lighting Research Technology, 39(1), 31-51

WONG, I. L., 2017. A review of daylighting design and implementation in buildings. Renewable and Sustainable Energy Reviews, 74, 959–968

WONG, N., ISTIADJI, A. & NG, E. 2004. Effect of external shading devices on daylighting penetration in residential buildings. Lighting Research and Technology, 36, 317-330.

WONG, N. H. & KHOO, S. S. 2003. Thermal comfort in classrooms in the tropics. Energy and Buildings, 35, 337-351.

WU, W. & NG, E. 2003. A review of the development of daylighting in schools. Lighting Research and Technology, 35, 111-124.

YAMTRAIPAT, N., KHEDARI, J. & HIRUNLABH, J. 2005. Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level. Solar Energy, 78, 504-517.

YANG, Z., BECERIK-GERBER, B. & MINO, L. 2013. A study on student perceptions of higher education classrooms: Impact of classroom attributes on student satisfaction and performance. Building and Environment, 70, 171-188.

YU, X., SU, Y. & CHEN, X. 2014. Application of RELUX simulation to investigate energy saving potential from daylighting in a new educational building in UK. Energy and Buildings, 74, 191–202

YUDELSON, J. 2007. Green Building, A to Z : Understanding the Language of Green Building, Gabriola Island, BC, CAN, New Society Publishers.

YUN, G., YOON, K. C. & KIM, K. S. 2014. The influence of shading control strategies on the visual comfort and energy demand of office buildings. Energy and Buildings, 84, 70-85.

ZAGREUS, L., HUIZENGA, C., ARENS, E. & LEHRER, D. 2004. Listening to the occupants: a Web-based indoor environmental quality survey. Indoor Air, 14, 65-74.

ZANNIN, P. H. T., KRÜGER, E. L. & DORIGO, A. L. 2008. Acoustic and luminous performance evaluations in classrooms in Curitiba, Brazil. Indoor and Built Environment, 17, 203-212.

ZURIGAT, Y. H., AL-HINAI, H., JUBRAN, B. A., AL-MASOUDI, Y. S., AL, HINAI, H. & MASOUDI, Y. S. 2003. Energy efficient building strategies for school buildings in Oman. International Journal of Energy Research, 27, 241.

Appendix A - Survey forms

Questionnaire 01: Visual Comfort Survey

Date ………/………/……… Time ………………
Condition …………………… Position …………

This survey is a part of visual comfort improvement of classrooms in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University. All information which has been provided will be treated confidentially and anonymous.

Section A: Personal information

1	Sex	□ M			□ F			
2	Age	□ <18		□ 18-22		□ >22		
3	Year	□ 1st year	□ 2nd year	□ 3rd year	□ 4th year	□ 5th year or others		
4	Weight	□ <40 kg.	□ 40-49 kg.	□ 50-59 kg.	□ 60-69 kg.	□ 70-79 kg.	□ 80-89 kg.	□ ≥ 90 kg.
5	Height	□ <150 cm.	□ 150-159 cm.	□ 160-169 cm.	□ 170-179 cm.	□ ≥180 cm.		
6	Eye condition (Note: vision problems such as myopia, presbyopia, astigmatism or others)							
	□ Normal				□ Have vision problems with eye glasses			
	□ Probably have vision problems				□ Have vision problems without eye glasses			

Section B: General Comfort

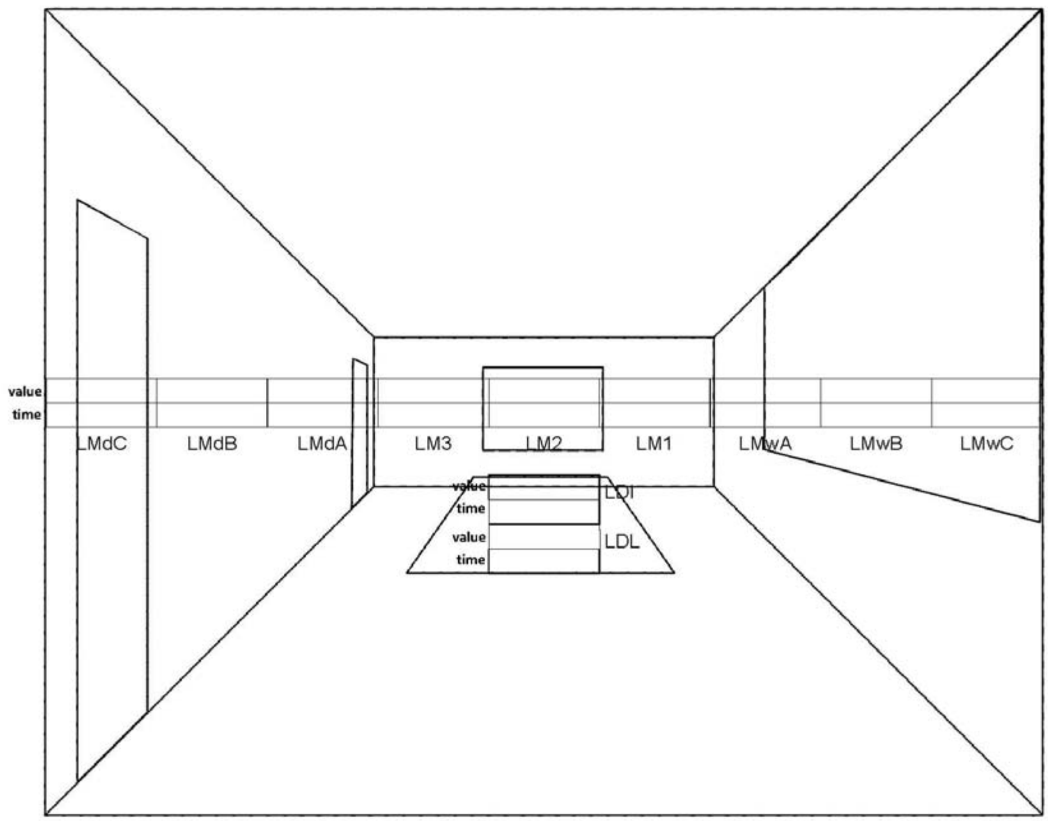
7	How do you feel the temperature at this time?						
	□ Much too warm	□ Too warm	□ Comfortably warm	□ Comfortable	□ Comfortably cool	□ Too cool	□ Much too cool
8	You would prefer to be		□ Much cooler	□ A bit cooler	□ No change	□ A bit warmer	□ Much warmer

Section C: Visual Comfort

9	How do you find the illumination level at this time?						
	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
10	You would prefer to be		□ Much brighter	□ A bit brighter	□ No change	□ A bit dimmer	□ Much dimmer
11	Is there too much glare in the room?			□ Yes	□ No	□ Don't know	

12	How satisfied are you with illumination level when reading text at your lecture desk?					
	□ Comfort	□ Discomfort				
		□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons
13	How satisfied are you with illumination level when reading text at the whiteboard?					
	□ Comfort	□ Discomfort				
		□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons
14	How satisfied are you with illumination level when reading text at the projector screen?					
	□ Comfort	□ Discomfort				
		□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reason

Measurement form: Visual Comfort Survey



Questionnaire 02: Satisfaction Survey

Date ……./……./…….

This survey is a part of visual comfort improvement of classrooms in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University. All information which has been provided will be treated confidentially and anonymous.

Section A: Personal information

1	Sex	□ M			□ F	
2	Age	□ <18		□ 18-22		□ >22
3	Year	□ 1st year	□ 2nd year	□ 3rd year	□ 4th year	□ 5th year or others
4	Which area in classrooms do you normally sit?					

the window

whiteboard			
	□ 1A	□ 1B	□ 1C
	□ 2A	□ 2B	□ 2C
	□ 3A	□ 3B	□ 3C

□ Not specific

Section B: Visual comfort

5	How do you feel the illumination level in your classrooms in general?						
	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
6	How would you rate the overall acceptability of the illumination level in your classrooms in general?						
	□ Acceptable			□ Not Acceptable			
7	How satisfied are you with illumination level when reading text at your lecture desk?						
	□ Very satisfied	□ Satisfied	□ Slightly satisfied	□ Neither satisfied nor dissatisfied	□ Slightly dissatisfied	□ Dissatisfied	□ Very dissatisfied
	Please describe issue……………………………………………………………………						
8	How satisfied are you with illumination level when reading text at the whiteboard?						
	□ Very satisfied	□ Satisfied	□ Slightly satisfied	□ Neither satisfied nor dissatisfied	□ Slightly dissatisfied	□ Dissatisfied	□ Very dissatisfied
	Please describe issue……………………………………………………………………						
9	How satisfied are you with illumination level when reading text at the projector screen?						
	□ Very satisfied	□ Satisfied	□ Slightly satisfied	□ Neither satisfied nor dissatisfied	□ Slightly dissatisfied	□ Dissatisfied	□ Very dissatisfied
	Please describe issue……………………………………………………………………						
10	Do you think natural light in classrooms is necessary to improve your motivation to learn and go to class?						
	□ Yes		□ No		□ Don't know		

11	How often you use natural light while studying in the classrooms?				
	□ Frequently	□ Almost frequently	□ Sometimes	□ Almost never	□ Never
12	How often the curtains were opened or closed while studying in the classrooms?				
	□ Frequently	□ Almost frequently	□ Sometimes	□ Almost never	□ Never
13	How often the electric lights turned on or off while studying in the classrooms?				
	□ Frequently	□ Almost frequently	□ Sometimes	□ Almost never	□ Never
14	Who normally controlled the curtains and electric light?				
	□ Teacher	□ Student	□ Both teacher and student	□ Faculty staff	□ Don't know

Section C: General comfort

15	How do you feel the temperature in your classrooms in general?						
	□ Much too warm	□ Too warm	□ Comfortably warm	□ Comfortable	□ Comfortably cool	□ Too cool	□ Much too cool
16	How would you rate the overall acceptability of the temperature in your classrooms in general?						
	□ Acceptable			□ Not Acceptable			
17	How would you rate your overall comfort in your classroom						
	□ Very satisfied	□ Satisfied	□ Slightly satisfied	□ Neither satisfied nor dissatisfied	□ Slightly dissatisfied	□ Dissatisfied	□ Very dissatisfied
18	Any other comment about classrooms						

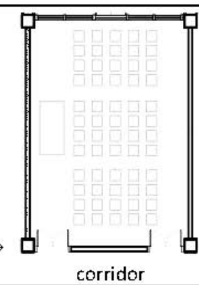
Questionnaire 03-1: Visual Comfort Survey (student)

This survey is a part of visual comfort improvement of classrooms in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University. All information which has been provided will be treated confidentially and anonymous.

Date ……/………/………

Time ………………

Position →



Section A: Personal information

1	Sex	□ M	□ F					
2	Age	□ <18	□ 18-22	□ >22				
3	Year	□ 1st year	□ 2nd year	□ 3rd year	□ 4th year	□ 5th year or others		
4	Weight	□ <40 kg.	□ 40-49 kg.	□ 50-59 kg.	□ 60-69 kg.	□ 70-79 kg.	□ 80-89 kg.	□ ≥ 90 kg.
5	Height	□ <150 cm.	□ 150-159 cm.	□ 160-169 cm.	□ 170-179 cm.	□ ≥180 cm.		
6	Eye condition (Note: vision problems such as myopia, presbyopia, astigmatism or others)	□ Normal						
	□ Probably have vision problems	□ Have vision problems with eye glasses	□ Have vision problems without eye glasses					
7	Your regular classroom (can select more than 1)	□ Auditorium	□ AR 204-208	□ AR 311-315	□ AR214, AR316	□ AR 213	□ others	

Section B: General Comfort

8	How do you feel the temperature at this time?	□ Much too warm	□ Too warm	□ Comfortably warm	□ Comfortable	□ Comfortably cool	□ Too cool	□ Much too cool
9	You would prefer to be	□ Much cooler	□ A bit cooler	□ No change	□ A bit warmer	□ Much warmer		

Section C: Visual Comfort: when the light is switched on.

10	How do you find the illumination level at this time?	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
11	You would prefer to be	□ Much brighter	□ A bit brighter	□ No change	□ A bit dimmer	□ Much dimmer		
12	Is there too much glare in the room?	□ Yes	□ No	□ Don't know				
13	How satisfied are you with illumination level when reading text at your **lecture desk?**	□ Comfort	□ Discomfort					
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons		
14	How satisfied are you with illumination level when reading text at the **whiteboard**?	□ Comfort	□ Discomfort					
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons		
15	How satisfied are you with illumination level when reading text at the **projector screen**?	□ Comfort	□ Discomfort					
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons		
16	When comparing to your regular classroom(s), please rate overall lighting environment of this room.							
	□ Better	□ The same	□ Worse	How? (if better or worse) …………………………				
17	Other comments about lighting environment when the light is switched on. ………………………… ………………………… …………………………							

Section D: Visual Comfort: when the light is switched off.

18	How do you find the illumination level at this time?	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim

19	You would prefer to be	□ Much brighter	□ A bit brighter	□ No change	□ A bit dimmer	□ Much dimmer
20	Is there too much glare in the room?			□ Yes	□ No	□ Don't know

21	How satisfied are you with illumination level when reading text at your **lecture desk?**					□ Comfort	□ Discomfort
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons	
22	How satisfied are you with illumination level when reading text at the **whiteboard**?					□ Comfort	□ Discomfort
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons	
23	How satisfied are you with illumination level when reading text at the **projector screen**?					□ Comfort	□ Discomfort
	Reason of discomfort	□ Too bright	□ Too dim	□ Veiling reflected	□ Not Clear task	□ Other reasons	

24	When comparing to your regular classroom(s), please rate overall lighting environment of this room.			
	□ Better	□ The same	□ Worse	How? (if better or worse) ....
25	Other comments about lighting environment when the light is switched off.			

Section E: Other comments and suggestions for improving classroom in general

26	....

Questionnaire 03-2: Visual Comfort Survey (lecturer)

Date ………/………./……… Time ………………

This survey is a part of visual comfort improvement of classrooms in Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University. All information which has been provided will be treated confidentially and anonymous.

Section A: Personal information

1	Name …………………………………………………					Department………………………	
2	Eye condition (Note: vision problems such as myopia, presbyopia, astigmatism or others)					□ Normal	
	□ Probably have vision problems	□ Have vision problems with eye glasses		□ Have vision problems without eye glasses			
3	Your regular classroom (can select more than 1)	□ Auditorium	□ AR 204-208	□ AR 311-315	□ AR214, AR316	□ AR 213	□ others

Section B: General Comfort

4	How do you feel the temperature at this time?	□ Much too warm	□ Too warm	□ Comfortably warm	□ Comfortable	□ Comfortably cool	□ Too cool	□ Much too cool
5	You would prefer to be	□ Much cooler	□ A bit cooler	□ No change	□ A bit warmer	□ Much warmer		

Section C: Visual Comfort: when the light is switched on.

6	How do you find the illumination level at this time?	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
7	You would prefer to be	□ Much brighter	□ A bit brighter	□ No change	□ A bit dimmer	□ Much dimmer		
8	Is there too much glare in the room?	□ Yes	□ No	□ Don't know				
9	When comparing to your regular classroom(s), please rate overall lighting environment of this room.							
	□ Better	□ The same	□ Worse	How? (if better or worse) ………………………………				
10	Other comments about lighting environment when the light is switched on. …………………………………… …………………………………… ……………………………………							

Section D: Visual Comfort: when the light is switched off.

11	How do you find the illumination level at this time?	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
12	You would prefer to be	□ Much brighter	□ A bit brighter	□ No change	□ A bit dimmer	□ Much dimmer		
13	Is there too much glare in the room?	□ Yes	□ No	□ Don't know				
14	When comparing to your regular classroom(s), please rate overall lighting environment of this room.							
	□ Better	□ The same	□ Worse	How? (if better or worse) ………………………………				
15	Other comments about lighting environment when the light is switched off. …………………………………… …………………………………… ……………………………………							

Section E: Other comments and suggestions for improving classroom in general

16	

Observation Form **No. ....** Date ..../........./........ Time ....

Room .... Subject .... Teacher .... Number of Students ......

Time	Use of			Facade operation		Participant			Note
	Whiteboard	Projector	Other devices	Curtain (open/partly open/close)	Electric light (on/partly on/off)	teacher	student	staff	....
Prep.									....
15 m.									
30 m.									
45 m.									
1 h.									
1.15 h.									
1.30 h.									
1.45 h.									
2 h.									
2.15 h.									
2.30 h.									
2.45 h.									
3 h.									
End									....

Comments:

....

....

....

Interview script **Teacher's name ………………………………** Date ……/………/……… Time ………………

Section A: Personal information

1	Sex	□ M			□ F					
2	Age	□ <25	□ 25-29	□ 30-34	□ 35-39	□ 40-44	□ 45-49	□ ≥ 50		
3	Teaching year	□ < 1 year	□ 1 - almost 2 years	□ 2 - almost 5 years	□ ≥ 5years					
4	Experience in this building	□ < 1 year	□ 1 - almost 2 years	□ 2 - almost 5 years	□ ≥ 5years					
5	Which room do you usually use in last semester?							□ AR204	□ AR205	□ AR206
	□ AR207	□ AR208	□ AR213	□ AR214	□ AR311	□ AR312	□ AR313	□ AR314	□ AR315	□ AR316

Section B: Visual comfort

6	Which condition do you arrange when teaching in general?	□ Partly open curtains /turn on electric lights					
	□ Never arrange anything	□ Partly open curtains /partly turn on electric lights					
	□ Not sure	□ Partly open curtains /turn off electric lights					
	□ Open curtains /turn on electric lights	□ Close curtains /turn on electric lights					
	□ Open curtains /partly turn on electric lights	□ Close curtains /partly turn on electric lights					
	□ Open curtains /turn off electric lights	□ Close curtains /urn off electric lights					
7	How do you feel the illumination level in your classrooms in general?						
	□ Very bright	□ Bright	□ Slightly bright	□ Neither bright nor dim	□ Slightly dim	□ Dim	□ Very dim
8	How would you rate the overall acceptability of the illumination level in your classrooms in general?						
	□ Acceptable	□ Not Acceptable					
	Please describe issue………………………………………………………………………………………………						
9	Which condition do you arrange when using projector?	□ Partly open curtains /turn on electric lights					
	□ Never arrange anything	□ Partly open curtains /partly turn on electric lights					
	□ Not sure	□ Partly open curtains /turn off electric lights					
	□ Open curtains /turn on electric lights	□ Close curtains /turn on electric lights					
	□ Open curtains /partly turn on electric lights	□ Close curtains /partly turn on electric lights					
	□ Open curtains /turn off electric lights	□ Close curtains /urn off electric lights					
10	How satisfied are you with illumination level when reading text at your teaching desk?						
	□ Very satisfied	□ Satisfied	□ Slightly satisfied	□ Neither satisfied nor dissatisfied	□ Slightly dissatisfied	□ Dissatisfied	□ Very dissatisfied
	Please describe issue………………………………………………………………………………………………						

11	How satisfied are you with illumination level when reading text at the computer screen?
	□ Very satisfied / □ Satisfied / □ Slightly satisfied / □ Neither satisfied nor dissatisfied / □ Slightly dissatisfied / □ Dissatisfied / □ Very dissatisfied
	Please describe issue..
12	How satisfied are you with illumination level when using whiteboard?
	□ Very satisfied / □ Satisfied / □ Slightly satisfied / □ Neither satisfied nor dissatisfied / □ Slightly dissatisfied / □ Dissatisfied / □ Very dissatisfied
	Please describe issue..
13	How satisfied are you with illumination level when using projector?
	□ Very satisfied / □ Satisfied / □ Slightly satisfied / □ Neither satisfied nor dissatisfied / □ Slightly dissatisfied / □ Dissatisfied / □ Very dissatisfied
	Please describe issue..
14	Do you think natural light in classrooms is necessary to improve learning performance?
	□ Yes / □ No / □ Don't know
15	How often you use natural light while teaching?
	□ Frequently / □ Almost frequently / □ Sometimes / □ Almost never / □ Never
	Please describe issue..
16	Do you operate or arrange to operate the curtains while teaching?
	□ Yes / □ No but students operate the curtain themselves / □ No, no one operates the curtain
17	How often the curtains were opened or closed while teaching?
	□ Frequently / □ Almost frequently / □ Sometimes / □ Almost never / □ Never
18	Why the curtains were operated?..
19	How the curtains were operated?..
20	Do you operate or arrange to operate the electric lights while teaching?
	□ Yes / □ No but students operate the curtain themselves / □ No, no one operates the curtain
21	How often the electric lights turned on or off while teaching?
	□ Frequently / □ Almost frequently / □ Sometimes / □ Almost never / □ Never
22	Why the electric lights were operated?...
23	How the electric lights were operated?...
24	Comments about daylighting in classrooms and user participation in system operation ....

Appendix B - Case study data

B-1 Survey summary

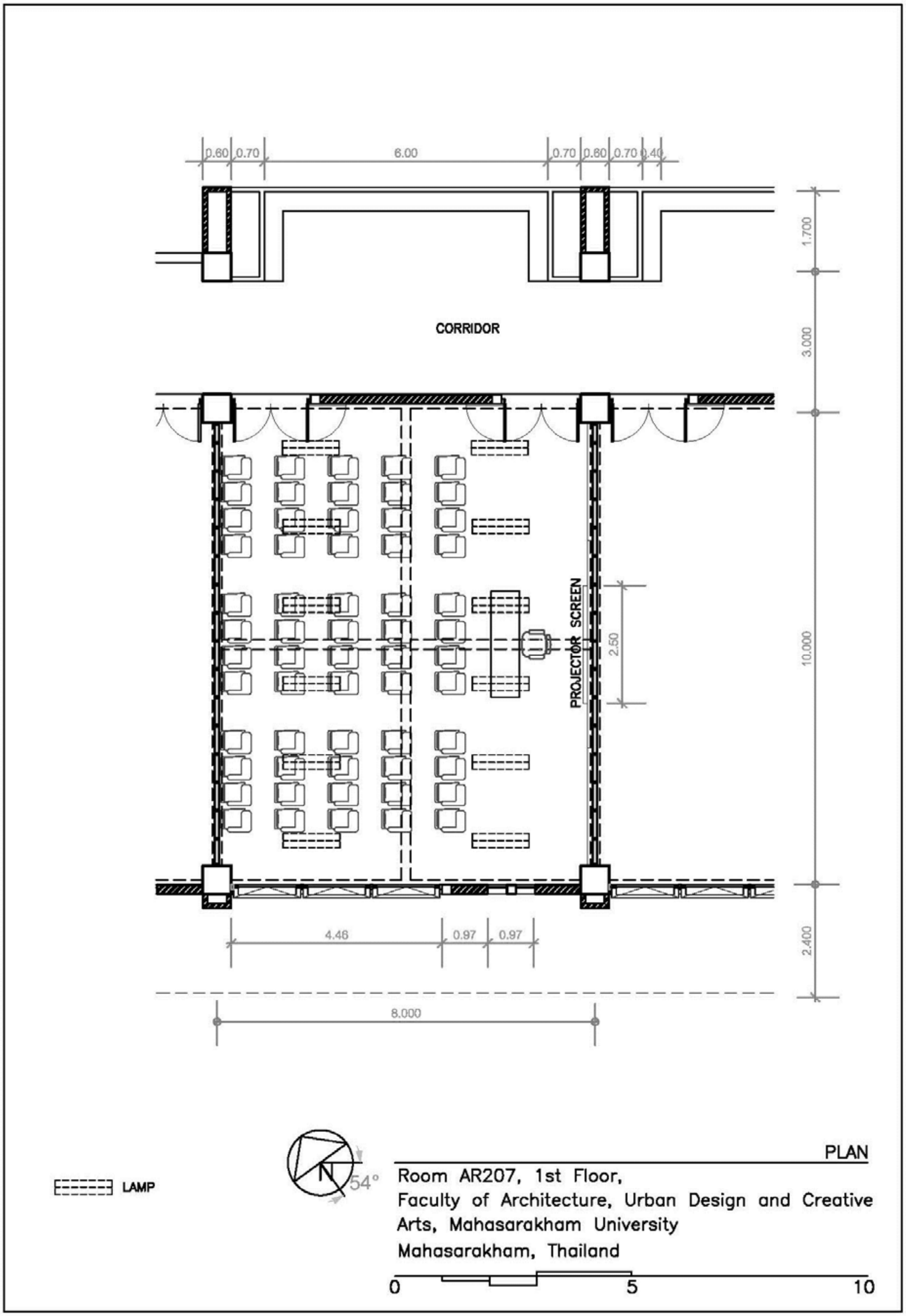
General info.		Owner		ARCH MSU	ARCH KKU	SC SWU	SC CRRU	PSU	AVG
		Room		AR207	SNP 3	1712	5111	5406 A	
		Survey date		3 March-19 May 16	18-19 May 16	11-12 April 16	8-9 March 16	16-17 March 16	
Architectural design parameter	Room size	Width: W (m.): side to side		10.20	9.90	16.00	8.40	7.65	10.43
		Length: L (m.): board to back		7.90	13.60	8.60	9.20	12.20	10.30
		Height: H (m.): ceiling height		3.50	3.00	3.00	2.70	3.00	3.04
		Floor area: A (m2)		80.58	134.64	137.60	77.28	93.33	104.69
		Window wall area		27.65	40.80	25.80	24.84	36.60	31.14
		W:L		1:0.77	1:1.37	1:0.54	1:1.10	1:1.59	1:1.08
		H:A		1:23.02	1:44.88	1:45.87	1:28.62	1:31.11	1:34.70
	Student seat	Number of seat: SN		60.00	69.00	73.00	53.00	73.00	65.60
		SN:A		1:1.34	1:1.95	1:1.88	1:1.46	1:1.28	1:1.58
		Number of row		5.00	7.00	5.00	5.00	8.00	6.00
		Avg. seat per row		12.00	10.00	15.00	12.00	11.00	12.00
		Orientation of seat to main window		right hand side	right hand side	left hand side	left hand side	right hand side	
	Aperture	Window orientation (normal CW)		SW (9°)	NW (2°)	E	N (5°)	NE (19°)	
		VSA of optimum shading		14	27	33	55	36	33.00
		Area of main window		9.54	23.2	6.875	6.76	4.5	10.18
		WWR (%)		34.50	56.86	26.65	27.21	12.30	31.50
		Total area of windows		11.05	59.40	9.66	14.84	15.50	22.09
		Shading device VSA		46.00	41.00	47.00	60.00	51.00	49.00
		Percentage of shading device to optimum shading device		57.89	77.78	75.44	85.71	72.22	73.81
		Glazing SC		0.79	0.79	0.79	0.48	0.48	0.67
		Type of internal shading device		orange fabric certain	dark brown fabric curtains	UV coated fabric curtains	none	none	
		Number of door		2	2	1	1	2	
		Total area of doors		7.90	5.6	3.2	1.6	5.4	4.74
	Classroom	Latitude		16.43N	16.47N	13.75N	19.99N	7.89N	
		Longitude		102.83E	102.83E	100.57E	99.85E	99.35E	
		Height (m.) of ground to floor		5.3	10.1	65	0.7	14	
		Distance (m.) from main window to obstruction		66	2.5	no surrounding	20	no surrounding	
		Environment outside main window		Walkway, road and parking	Trees	Condensing units	Road, parking and a building	Trees	
	Corridor	Width of corridor		2.4	2.2	3	1.7	2.65	2.39
		Wide of other corridor elements		2	0	0	0.6	13.25	3.17
		Total width of corridor		4.4	2.2	3	2.3	15.9	5.56
		Exposure to outside environment		opened	opened	closed corridor with windows	opened	closed corridor with windows	
		Environment outside corridor		open court	open space	open space	open space	open court	
	Decoration	Colour	Floor	white	light brown	white	light brown	light brown	
			Wall	yellow(front)/ grey	grey/ brick	white/ silver curtain	white	white	
			Ceiling	white	white	white	white	white	
		Surface texture	Floor	glossy	glossy	semi-glossy	glossy	glossy	
			Wall	matt	matt	matt/ semi-glossy	matt	matt	
			Ceiling	matt	matt	matt	matt	matt	
		Finishing materials	Floor	concrete+mortar+painting	vinyle tile	Terrazzo	vinyle tile	vinyle tile	
			Wall	brick+mortar+painting	brick+mortar+painting	brick+mortar+painting/ glazing	brick+mortar+painting	brick+mortar+painting	
			Ceiling	No ceiling/ concrete+mortar+painting	Flat/ Gypsum board	T-bar/ Gypsum board+Aluminium frame	Flat/ Gypsum board	T-bar/ Gypsum board+Aluminium frame	
	Building system	Type of A/C		Split type+ fan	Split type	Central+Split type	Split type+ fan	Split type	
		Type of light bulb and lamp		2 fluorescents in mounted lamp with aluminium louvers and reflectors	2 fluorescents in built-in lamp with aluminium louvers and reflectors	2 fluorescents in white mounted lamp	2 fluorescents in built-in lamp with diffused acrylic diffussed cover	4 fluorescents in built-in lamp with aluminium louvers and reflectors	

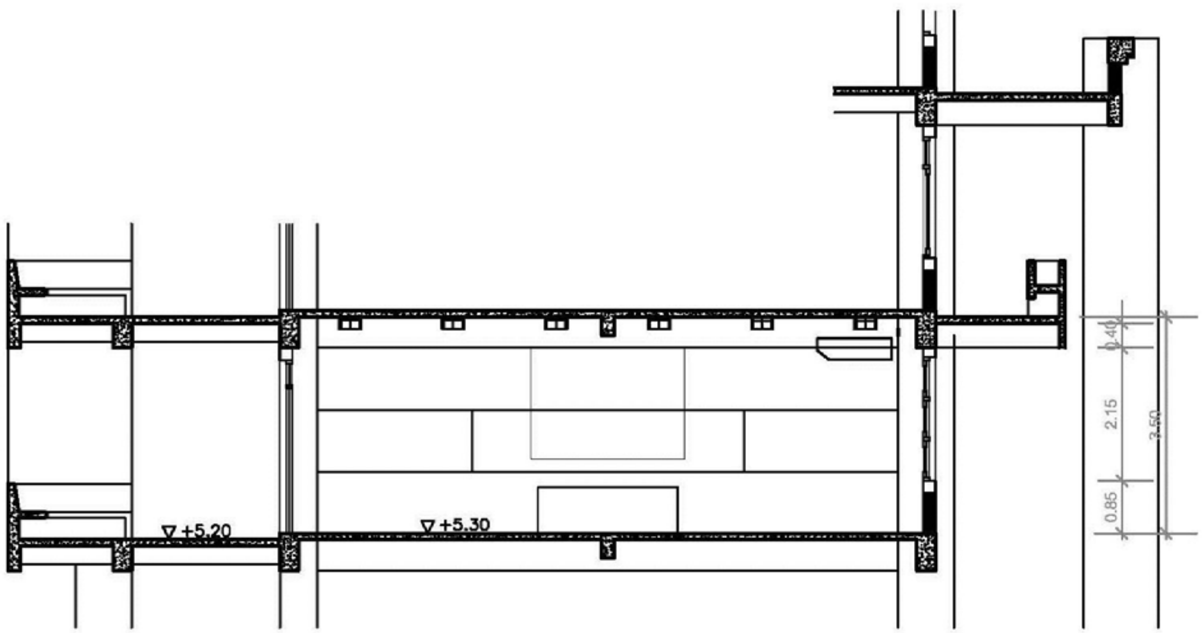
General info.		Owner	ARCH MSU	ARCH KKU	SC SWU	SC CRRU	PSU	AVG
		Room	AR207	SNP 3	1712	5111	5406 A	
		Survey date	3 March-19 May 16	18-19 May 16	11-12 April 16	8-9 March 16	16-17 March 16	
		Lighting lay out	grid of 6x2 lamps	grid of 3x3 lamps	grid of 6x3 lamps	grid of 4x2 lamps	grid of 3x5 lamps	
IEQ parameter	Visual comfort	Positive attitude in daylighting (%)	71.92	84.81	60.00	79.53	64.00	72.05
		Natural light use frequency (%)	51.78	51.52	46.13	64.44	51.68	53.11
		Brightness sensation (%)	82.29	75.95	75.05	76.44	76.40	77.23
		Brightness acceptability rate (%)	98.63	99.37	99.33	95.91	90.00	96.65
		Max. external illuminance (lux)	25,152.35	32,644.87	5,042.85	5,648.72	5,561.04	14,809.96
		Min. external illuminance (lux)	1,560.17	11.93	2,013.09	3,711.37	1,805.88	1,820.49
		Min. internal illuminance (lux)	12.96	12.96	12.96	190.78	21.19	50.17
		Visual comfort (%) lecture desk	86.99	89.87	87.33	84.21	93.60	88.40
		Visual comfort (%) whiteboard	63.70	58.86	50.00	67.84	82.40	64.56
		Visual comfort (%) projector screen	54.79	54.43	39.33	63.74	73.20	57.10
	Thermal comfort	Thermal sensation (%)	55.28	51.36	50.19	73.77	54.40	57.00
		Max. outdoor temperature (°C)	41.34	44.72	33.70	34.47	34.15	37.68
		Min. outdoor temperature (°C)	24.07	25.67	30.75	22.66	30.47	26.72
		Max. indoor temperature without A/C in working hour (°C)	33.60	33.02	29.69	31.73	29.53	31.51
		Max. outdoor RH (%)	79.24	82.30	69.96	65.90	68.18	73.11
		Min. outdoor RH (%)	28.42	36.01	49.00	26.20	48.78	37.68
		Average indoor RH in working hours (%)	57.60	63.12	67.48	52.49	56.50	59.44
		Thermal acceptability rate (%)	95.21	95.57	96.67	71.93	83.20	88.51
Overall satisfaction			80.72	72.24	73.71	68.92	79.94	75.11

B-2 Appearance

Classroom	Classroom	Corridor	Outside	Building
ARCH MSU AR207				
ARCH KKU SNP3				
SC SWU 1712				
SC CRRU 5111				
PSU 5406A				

B-3 Architectural drawing

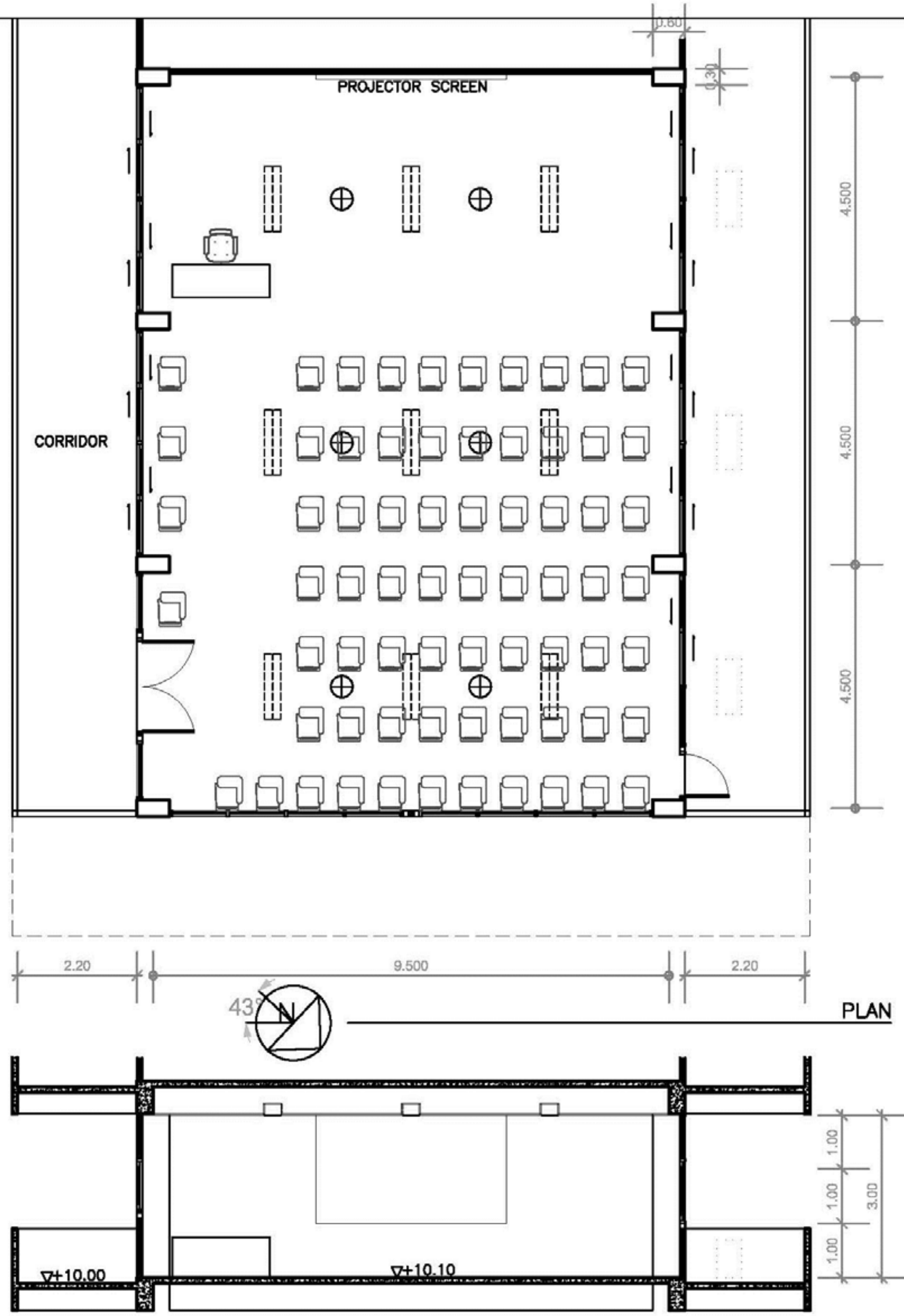




CROSS SECTION

Room AR207, 1st Floor,
Faculty of Architecture, Urban Design and Creative Arts, Mahasarakham University
Mahasarakham, Thailand

0 5 10

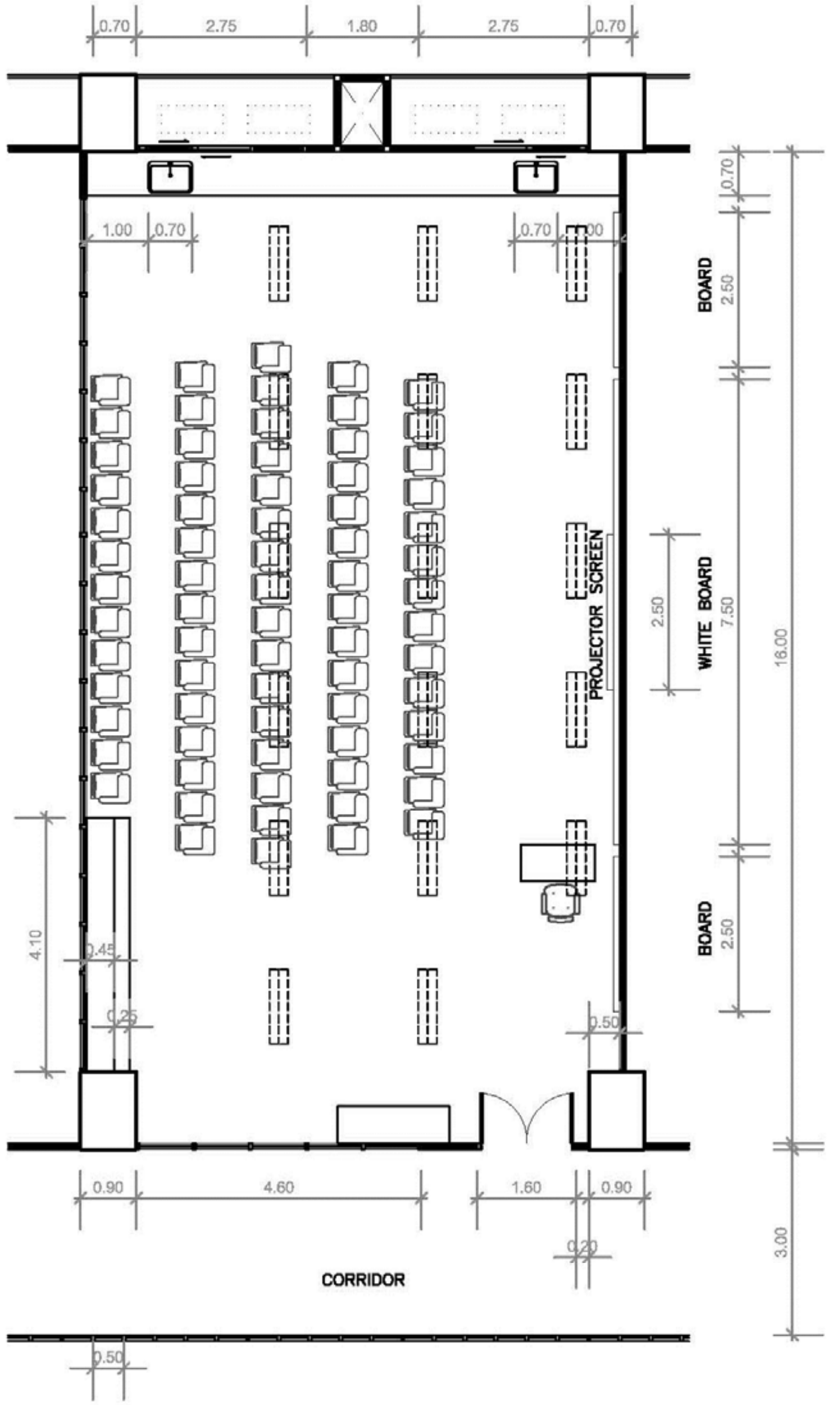


CROSS SECTION

LAMP
ELECTRIC FAN
CONDENSING UNIT

Room SNP3, 2nd Floor,
Sohnohpoh Building
Faculty of Architecture, Khon Kaen University
Khon Kaen, Thailand

0 5 10



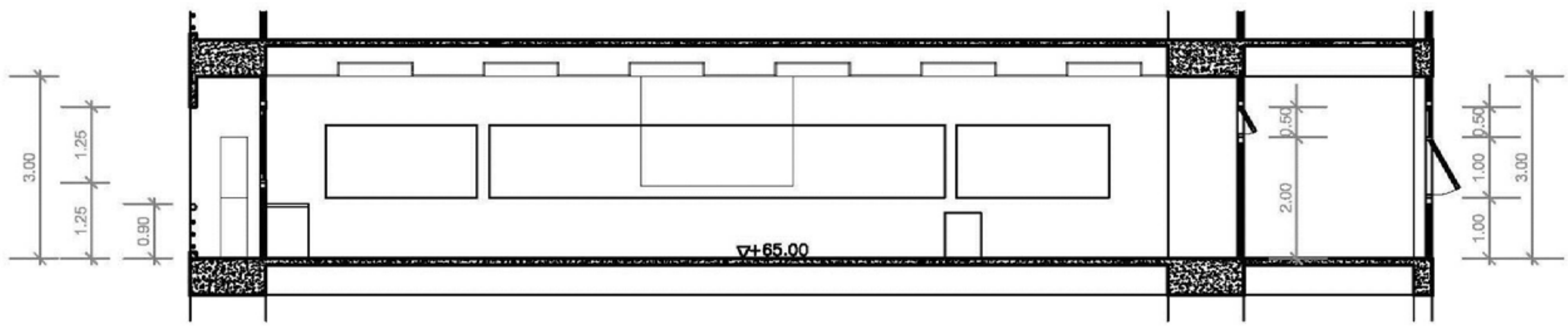
LAMP

CONDENSING UNIT

PLAN

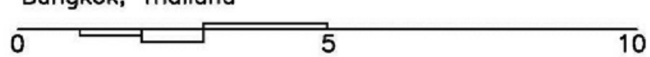
Room 1712, 16th Floor,
Building no.19, Department of General Sciences
Faculty of Sciences, Srinakharinwirot University
Bangkok, Thailand

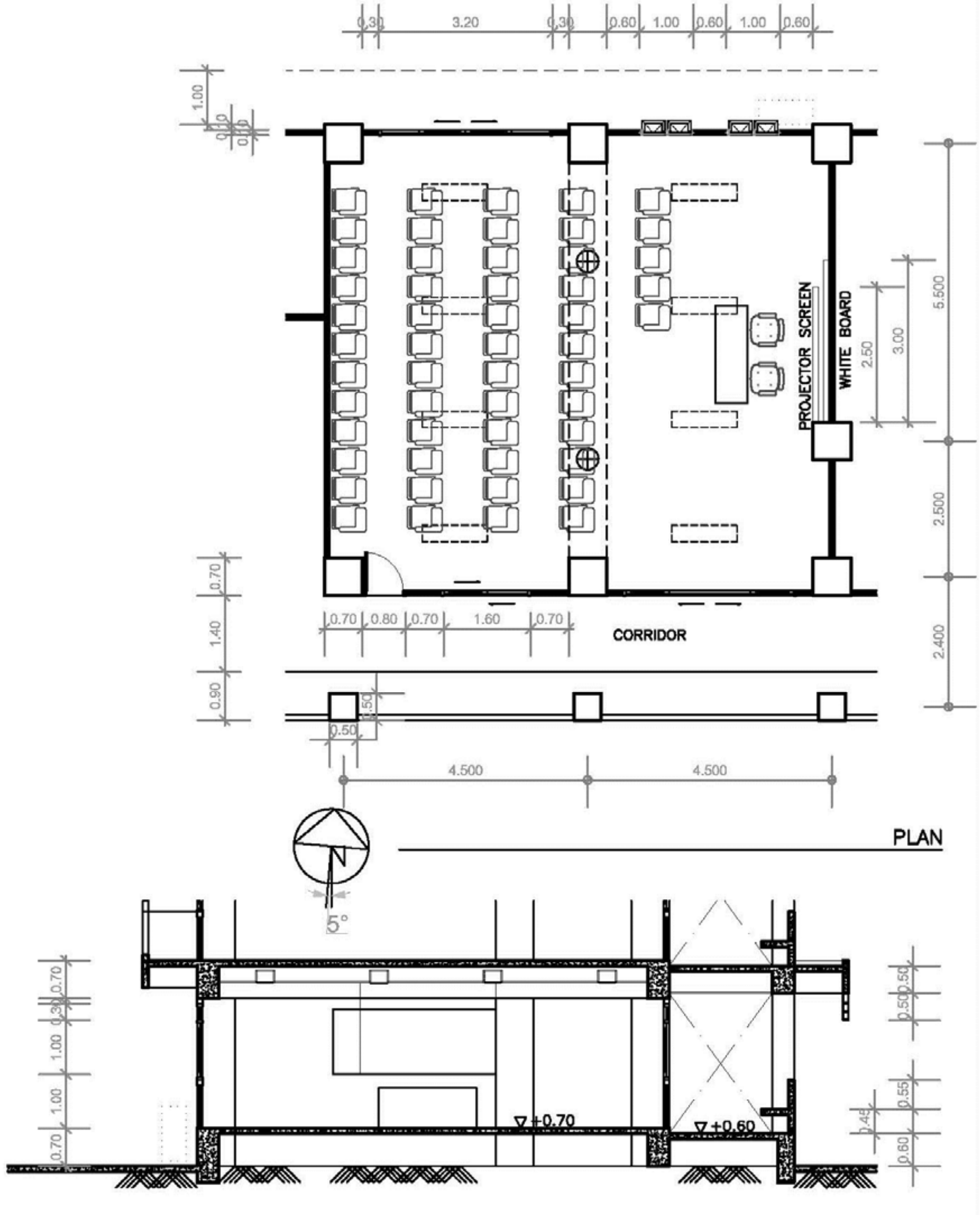
0 5 10



CROSS SECTION

Room 1712, 16th Floor,
Building no.19, Department of General Sciences
Faculty of Sciences, Srinakharinwirot University
Bangkok, Thailand





CROSS SECTION

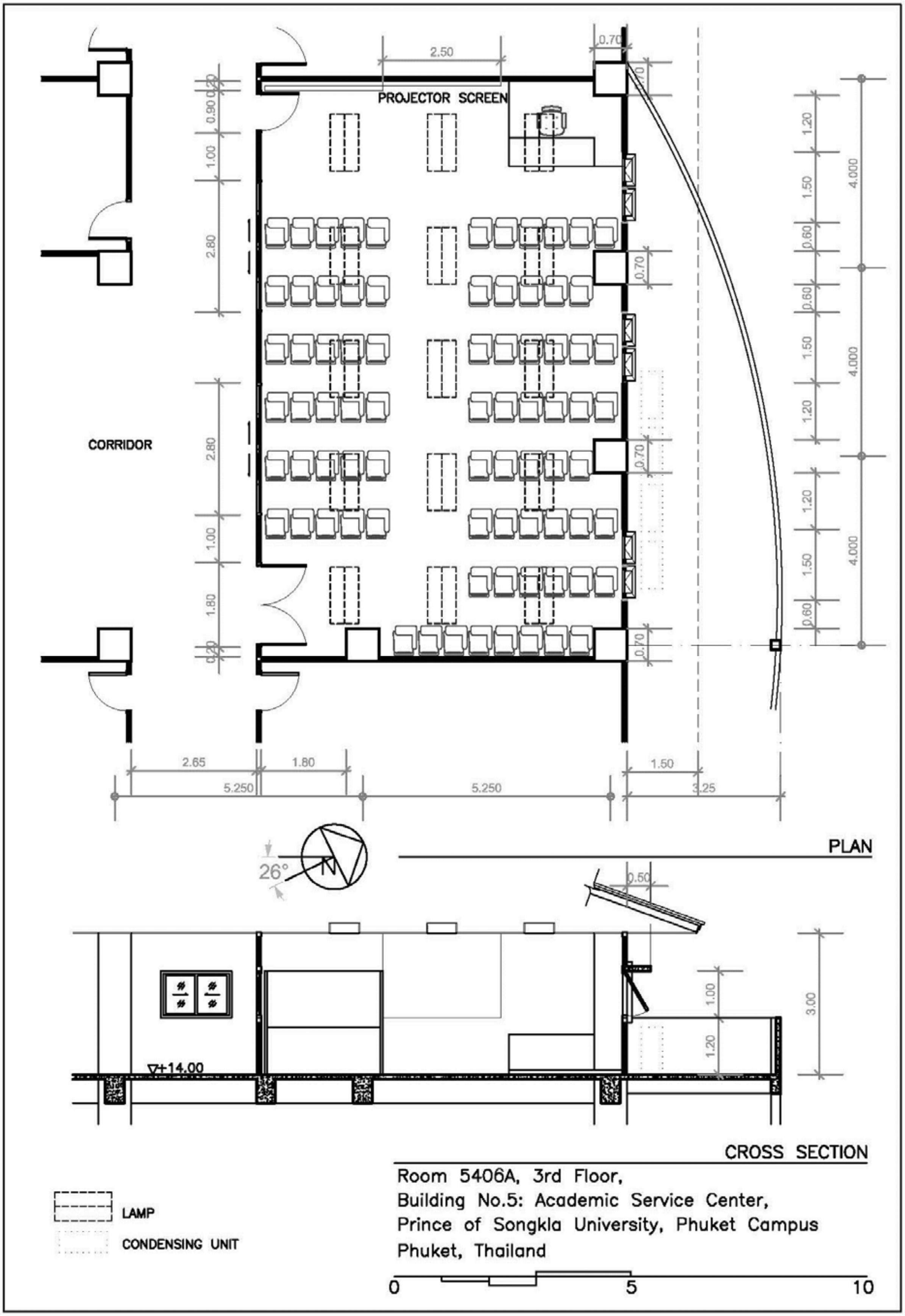
LAMP

ELECTRIC FAN

CONDENSING UNIT

Room 5111, Ground Floor,
Math Building, Faculty of Sciences and Technology
Chiang Rai Rajabhat University
Chiangrai, Thailand

0 5 10



PROJECTOR SCREEN
2.50
0.70
CORRIDOR
1.20
1.50
0.60
4.000
2.80
1.00
1.80
2.65
5.250
1.50
3.25
26°
N
PLAN
0.50
1.00
1.20
3.00
▽+14.00
CROSS SECTION
Room 5406A, 3rd Floor,
Building No.5: Academic Service Center,
Prince of Songkla University, Phuket Campus
Phuket, Thailand
LAMP
CONDENSING UNIT
0
5
10